An Integrated Analysis of Collaborative Design Processes

Thesis

An Integrated Analysis of Collaborative Design Processes

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Abstract

This thesis makes a contribution to the understanding of designerly ways of solving problems by exploring the central question of how different prototyping materials affect collaborative design processes, especially with regard to the co-construction of knowledge and the social dynamics manifested in verbal and non-verbal behaviour. The thesis also contributes to the existing knowledge by offering a new method to analyse the role of prototypes in collaborative design activities: Proxemic Motion Trace Analysis.

Understanding the relationship between prototypes and design processes is important in the light of an increasing interest in using design-based approaches to develop innovations, and thus to better understand the design process itself. However, what role prototypes and prototyping materials play in collaborative design processes, particularly in verbal and non-verbal interactions, remains an under-researched area.

The thesis comprises two main studies: a series of unstructured field observations, conducted at four design studios, and an academic institution, and a series of 23 controlled experiments consisting of 99 individual design tasks conducted with design students at Central Saint Martins College of Arts and Design.

The key findings demonstrate that: (1) different prototyping materials affect qualitative aspects of verbal and non-verbal behaviour in collaborative design activities in distinguishable ways; (2) specific materials allow for a more connected co-construction of knowledge; and (3) the research undertaken has produced a new and design-specific method of analysing collaborative design processes, especially the verbal and non-verbal behaviour of designers.

It is suggested that these findings have implications for design practice and design education, as well as other professions using designerly ways of solving problems. In addition, the newly developed visual method of analysing design collaboration provides potential for future design research by providing a method that addresses the full complexity of interaction in design collaboration.

Declaration

This is to certify that:

the thesis comprises only my original work towards the PhD except where indicated, due acknowledgment has been made in the text to all other material used, and the thesis is less than 100,000 words in length, inclusive of all footnotes, bibliographies and appendices

Andreas Peter

May 2015

Publications & Conference Proceedings

Two peer-reviewed conference publications have been written in the course of this PhD and are incorporated in this thesis:

Peter, A., Schadewitz, N., and Lloyd, P. (2011). Talk Around Things: Prototyping and Discussion in the Design Process. *Proceedings of the International Association of Societies in Design Research Conference (IASDR 2011)*, TU Delft, The Netherlands.

Peter, A., Lotz, N., McDonnell, J., and Lloyd, P. (2013). The Effect of Prototyping Material on Verbal and Non-verbal Behaviours in Collaborative Design Tasks. *Proceedings of the International Association of Societies in Design Research Conference (IASDR 2013)*, Shibaura Institute of Technology, Tokyo, Japan.

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1

1 Preface

"Engineering, medicine, business, architecture and painting are concerned not with the necessary but with the contingent – not with how things are but with how they might be – in short, with design."

Herbert Simon

1.1 Setting the scene

In a controversial speech given at the Parsons School in 2007, titled "Are Designers The Enemy Of Design?" the influential design journalist, Bruce Nussbaum, took a provocative stance:

> DESIGNERS SUCK. There's a big backlash against design going on today and it's because designers suck. So let me tell you why. Designers suck because they are arrogant. The blogs and websites are full of designers shouting how awful it is that now, thanks to Macs, Web 2.0, even YouTube, EVERYONE is a designer. [...] Designers are saying that Design is everywhere, done by everyone. So Design is debased, eroded, insulted. The subtext, of course, is that real design can only be done by great star designers (Nussbaum, 2007).

How designers work and solve problems has been a subject of scientific inquiry since the design methods movement in the 1960s. In the past decade, however, and in the light of an increasing demand for new approaches in innovation development, interest in designerly ways of thinking has been renewed and spread to other fields of expertise and scientific research. Today, designing and design thinking are often regarded as a capacity not exclusively attributed to designers, architects or engineers, but, to a certain degree, to almost all professions. In fact, the tools and techniques of designers, as Nussbaum has observed, have become largely democratised. Particularly in the management domain, the demand to think like designers has been promoted and adopted emphatically in recent years. Consequently, individual aspects of designing have found their way into not only educational curricula, but also professional practice outside the traditional design world.

As with profound change in any field, this has not gone without significant resistance. Designers are not the only ones naturally aiming to defend their turf when it boils down to a paradigmatic reorientation of their discipline. However, despite its perceived threat, this development somehow represents an opportunity for the design discipline. Cross (2006) has stated before that "design ability is a multi-faceted cognitive skill, possessed in some degree by everyone" (p. 41). He even suggests the possibility to claim that design ability might be a form of natural intelligence. As with every kind of intelligence, there are some who are endowed with more and some with less of it. And there are those who hone and nurture their skills to become even more intelligent. To contemplate design ability in this context not only renews and reinforces the interest in how ways of thinking specific to designers may be understood in more depth, but makes this endeavour highly relevant for today's design practice, theory and beyond.

1.2 Artefacts and collaboration

In the public perception, designers are still largely thought of as lone geniuses, working secretly and in obscure ways on objects of beauty – which may or may not be the new Apple iPhone, Lamborghini or B&O stereo. While design work is still often carried out in secrecy, in today's world of converging technologies, consumer research and market strategizing, the days of the lone genius seem to be far gone. Answering to an increased need for interdisciplinary work in practice, collaboration across and within disciplines is the daily routine of designers nowadays (Buchenau & Suri, 2000).

Collaboration in design processes can take on many forms. It can, for example, occur as remote collaboration supported by sophisticated software, or as asynchronical collaboration with different designers working in different time zones on a shared solution. However, still the most prevailing form of design collaboration takes place when people sit down to discuss prototypes. Discussions in design processes can be understood merely as a means of social interaction, contributing to the exchange of information and to team maintenance and cohesion. They can, however, also be viewed as an integral part of designing, where meaning is collectively being negotiated, or, as Lloyd and Busby (2001) argue, where "a kind of 'world' is being constructed" (p. 68). When thought of not only as a way of conveying information, analysing conversations occurring in collaborative design processes – especially when supported by artefacts – allows us to gain a deeper understanding of how people use designerly ways of thinking to solve problems. Bucciarelli (1994) emphasises this interrelation of the social and artefact-based dimensions of designing when proposing that "it is the object as they [the designers] see and work with it that patterns their thought and practice" (p. 4).

When taking a closer look at just how collaborative activities in design processes are being carried out, the importance of prototypes becomes evident. Prototyping in a general sense – be it in two dimensions when sketching, or three dimensions when, for example, working on a clay model – seems to be the most ubiquitous design activity. Designers use it not only to present design solutions, but as a means of supporting and enabling the thought-process individually and collectively. Somewhat surprisingly then, just how these artefacts relate to the ways they are collaboratively negotiated and developed in multi-modal design conversations remains an issue which is not thoroughly understood yet.

1.3 Research questions

Although prototypes and their social functions are crucial to every design process and design collaboration, only a small amount of research relates the various forms of artefacts to their roles in social interaction. In designing complex products, interdisciplinary collaboration is crucial to developing design solutions successfully. While prototyping and collaboration as pervasive activities in all design disciplines essentially shape what is being designed, just how these two aspects interrelate represents an under-researched area. This thesis tries to fill this gap in the existing literature and to gain insights that are highly relevant for design practice. Thus, this thesis investigates phenomena at the intersection between those two key facets of designing. The core research question asked is:

How do different types of prototyping media contribute to collaborative design processes, particularly the 'quality' of verbal and non-verbal interaction?

Underlying the research question are the following hypotheses that guide the research:

(1) Different kinds of prototyping media inform qualitative aspects of social dynamics in collaborative design processes.

(2) Different kinds of prototyping media inform the co-construction of knowledge in collaborative design processes.

1.4 Structure of the thesis

The investigation undertaken in the context of this research started with an unstructured field observation of design practice. The aim was to discern how design was actually accomplished in professional design studios and what issues are prevalent within this context. The focus was on different uses of prototypes and their relations to design discussions. Based upon the findings, more specific questions arose that required a more structured observation. These questions were addressed in a series of experiments that allowed for a more isolated observation and analysis. The thesis is structured into six main parts: (a) the theoretical framework, (b) the methodological reflections, (c) the evolution of the new methodology from practice studies and pilot studies, (d) the description of the Proxemic Motion Trace Analysis, (e) the research results, and (f) the conclusion.

The first part aims at providing the underlying framework upon which this research builds. It starts out by observing design activities and artefacts in practice. Inspired by these findings, it first explores how design researchers have tried to understand the specific designerly ways of thinking. It then describes how the existing research understands designing both as a social activity and as a prototyping activity. What is known about these two dimensions, particularly about artefacts and verbal and non-verbal interaction, is then drawn together.

Just why a new method to investigate design processes is needed constitutes the second part of the thesis. The aim of design research is restated to provide the general backdrop for the reflections in this chapter. The most relevant design research methods are reviewed and their advantages and shortcomings summarised, demonstrating the need for a new method.

The third main chapter recounts the approach and findings leading up to the development of a new method to analyse collaborative design processes. It shows how insights gained in different practice studies necessitated a series of pilot studies, which evolved over the course of this thesis into the new method.

The fourth part describes in detail how the new method – the Proxemic Motion Trace Analysis PMTA – works and how it can be applied to provide a comprehensive view of collaborative design processes.

The results of the research activities and the application of the PMTA are presented in the fifth chapter. It reports the findings gained from a series of 23 experiments using the Proxemic Motion Trace Analysis.

The sixth chapter interprets and discusses the results gained from analysing prototyping and interaction using PMTA. It gives possible explanations for the observations made and relates them to the existing literature.

The final chapter proposes the conclusions from the research. Furthermore, it reflects on the limitations of this thesis, on possible implications for design practice as well as design theory and provides an outlook to future work.

2

2 Literature review

This chapter critically explores the existing literature around prototyping and collaboration, particularly in regard to the social and artefact-related dimensions of designing. In a first step, it tries to better understand why prototypes are crucial to designing, what we know about them and about their role in collaborative processes. The chapter then looks at how prototypes relate to the social dimensions of design collaboration, particularly what the literature proposes about the specific verbal and non-verbal behaviour in artefact-centred interactions and what we know and do not know about the role prototypes play in social interactions in artefact-facilitated conversations.

2.1 Designing as prototyping activity

2.1.1 Why prototypes matter

Cross (2011) highlights the importance prototyping plays in the work of outstanding designers. Reporting the development of a city car by the eminent car designer Gordon Murray, he recounts that "the design work took a major step forward when Gordon and his team built a very simple, full-size mock-up of the car, using wire and cardboard. [...] The mock-up became a useful design tool, as it began to suggest some new possibilities" (p. 47). Cross observes a similar approach in the design practice of another outstanding designer, Kenneth Grange. For one early and important work of his, a food mixer for Kenwood, Grange accounts that he "did everything with model-making" (p. 66).

This emphasis of prototypes in design work is not a singular observation. Perry and Sanderson (1998) claim that "design and engineering is constructed through the interactions of multiple actors", and highlight that "artefacts and representations of the design process have a key function in the organisation of this work" (p. 273). Edelman, Leifer, Banerjee, Jung and Sonalkar (2009) echo this perspective, proposing that "the media which design engineers enlist are cognitive tools which extend and modify their ability to perceive, think and communicate" (p. 395). More generally, they argue that: "Design thinking and communication occur in the presence of representation. It is through representation that group members can literally see what they say and reflect on what they see" (p. 395). This corroborates the crucial role design objects play in designing activities by informing thought and communication processes. Most models of design thinking emphasise the role of prototyping and collaboration as crucial features of design activity too (Rowe, 1987; Kelley, 2001; Lawson, 2005; Cross, 2006; Brown, 2009). Bucciarelli (1994) supports this claim by observing: "To participants in design, the object serves as a kind of icon that embodies a set of attitudes and ways of thinking that are peculiar to engineering" (p. 2). He emphasises that "it is the object as they see and work with it that patterns their thought and practice" (p. 4). Analysing social interactions in the Delft Protocol Analysis Workshop, Brereton, Cannon, Mabogunje and Leifer (1996) support this perspective:

> Many solution proposals and interpretations of requirements clearly arise from designers' interacting with available hardware. [...] A compelling analysis would also result from examining how hardware acts as a negotiator to steer the activity (p. 339).

There is a general consensus in the existing literature about the importance of prototypes and artefacts in design work and their role in facilitating collaboration. However, it does not explain just what role prototypes play in design collaboration and in what ways they facilitate the process. This points to one of the central aims of this thesis: to better understand how artefacts relate to the types of collaborative design activity that lead up to the development of final design solutions.

2.1.2 Prototypes as boundary objects negotiating between fields of expertise

The literature above implicitly points to the collaborative nature of today's design activities. Indeed many argue that designing has become an increasingly collaborative activity (Buchenau and Suri, 2000; Feast, 2012; Smulders et al., 2008; Adamst et al., 2009). Such a view is supported, for example, by Trevelyan (2000) advancing that the foundation of design practice "is distributed expertise enacted through social interactions between people" (p. 177). Perry and Sanderson (1998) too, point to the importance of collaborative design activity: "design and engineering is constructed through the interactions of multiple actors" (p. 273). Design objects inform not only the way individual designers work, but also how teams negotiate their way to a design solution.

The concept of boundary objects, first introduced by Star and Griesemer (1989), underlines this understanding of design artefacts. By representing, translating and facilitating knowledge, concepts and ideas across the frontiers of individual disciplines, prototypes may be defined as boundary objects. Star and Griesemer define boundary objects as:

> [B]oth plastic enough to adapt to local needs and constraints of the several parties employing them, yet robust enough to maintain a common identity across sites. They are weakly structured in common use, and become strongly structured in individual-site use. They may be abstract or concrete. They have different meanings in different social worlds but their structure is common enough to more than one world to make them recognizable, a means of translation. The creation and management of boundary objects is key in developing and maintaining coherence across intersecting social worlds (p. 393).

Carlile (2002) developed the concept of boundary objects further. He lists three characteristics of 'effective' boundary objects in new product development: (1) "a boundary object establishes a shared syntax or language for individuals to represent their knowledge"; (2) "an effective boundary object at a semantic boundary provides a concrete means for individuals to specify and learn about their differences and dependencies across a given boundary"; and (3) "an effective boundary object facilitates a process were individuals can jointly transform their knowledge" (p. 452).

Related to the concept of boundary objects, Wenger (1996) has put forward the concept of 'communities of practice' as crucial to organisational knowledge management and as, in fact, the "social fabric of knowledge" (Wenger, 2004, p. 1). Such communities are essentially groups of people who are informally bound together by a shared expertise and a commitment to a shared cause. Wenger emphasises that "Knowing is not merely an individual experience, but one of exchanging and contributing to the knowledge of a community" (p. 1). This observation is especially relevant in today's design practice which needs to incorporate various bodies of knowledge in order to develop comprehensive design solutions. In this context, Wenger's observation that artefacts are not only valued in individual communities, but that they "support connections between different practices" (Wenger, 2000, p. 236) is pertinent. He differentiates between three kinds of boundary objects: (1) artefacts (e.g. tools, documents or prototypes); (2) discourses (e.g. languages or jargons); and (3) processes (e.g. explicit routines or business processes). However, boundary objects do not ensure a working exchange of knowledge per se. Wenger notes that they "do not necessarily bridge across boundaries because they may be misinterpreted or interpreted blindly" instead, they "enable multiple practices to negotiate their relationships and connect their perspectives" (p. 236).

This characterisation gives an insight into the key functions design objects provide in collaborative design activities: they act as a shared language in which different team members can communicate, negotiate and evaluate. They help to specify differences and dependencies between individual domain-specific interpretations, and they facilitate collaborative negotiation of the design solution. These features are of crucial importance when considering that the "problem facing cross-functional design teams is one of distributed cognition. [...] Much of their knowledge can be said to reside in representations that team members create for and share with one another" (Edelman et al., 2009, p. 396). In order to provide these functions and to facilitate knowledge transfer and joint knowledge transformation, design objects as boundary objects may take on different forms according to their purpose or location within the design process. As illustrated above, the existing literature tells us about the importance and role prototypes and artefacts play in collaborative design processes. It does not, however, explain how different types of prototypes contribute in what ways to those processes. It begs the question as to whether all kinds of artefacts inform design collaboration in the same way, or whether there are differences. To better understand the potentially different roles of boundary objects in design collaboration, one has to first understand what different kinds of prototypes are used in design practice.

2.1.3 Typologies of prototypes

In the literature, different kinds of prototypes have been categorised along various dimensions. Most of them can be roughly summarised into two categorisations: one focusing on 'functions and purposes' of prototypes, and one on the 'developmental stages' prototypes are being employed in.

Function & purpose

Ullman (2003) focuses on the individual purposes prototypes serve: (1) proof-of-concept prototypes, which test the basic concept and clarify the initial design approach; (2) proof-of-product prototypes, which are to test the actual artefact and define the product's physical embodiment; (3) proof-of-process prototypes, which verify a specific sequence of actions or production methods and materials that will result in the desired product; and (4) proof-of-production prototypes, which are to clarify the possibilities or problems faced in the complete production process of the artefact. Focusing on proof-of-concept prototypes, Houde and Hill (1997) propose a triangle model, incorporating the three dimensions: 'role', 'function' and 'form'. According to Houde and Hill prototypes might show one of these dimensions or all three together, while artefacts incorporating all three dimensions are considered integration prototypes.

Pei, Evans and Campbell (2011) propose an extended taxonomy for sketches, drawings, models, and prototypes. Pei et al. define sketches as preliminary design representations without detail, and drawings as a structured, formal arrangement of lines. While this distinction is relatively clear, the difference between models and prototypes is less so. The authors make the distinction between appearance models (industrial design models) and functional models (engineering models). However, Pei et al. propose the same classification for prototypes (industrial design prototypes and engineering design prototypes).

Budde et al. (1992) propose another classification, orienting itself on the purpose and the manner of construction of the prototypes: (1) presentation prototype, which is used for presentations to convince clients of the feasibility; (2) prototype proper, which is built and tested to clarify user needs; (3) breadboard prototype, which is built to ensure the technical feasibility; and (4) pilot system prototype, which represents the core solution and can be, after a few iterations of evolutionary prototyping, serve as a final design solution.

Developmental stage

Another categorisation is proposed by Sommerville (1995) and Budde et al. (1992). Both suggest considering the stages of prototype development. According to this categorisation, Sommerville identifies three stages: 'throwaway', 'evolutionary' and 'incremental'. Similarly, Budde et al. describe the stages as 'evolutionary', 'experimental' and 'exploratory'.

Edelman and Currano (2011) propose to categorise design objects within a matrix with the two dimensions 'resolution' (the level of refinement or granularity) and 'abstraction' (the degree to which specific characteristics are pulled out of context). They distinguish between three types of design objects: (1) ambiguous media, such as rough sketches and physical prototypes, which are argued to encourage divergent conversations and paradigmatic changes; (2) mathematised media, such as highly realistic images or technical drawings, which are argued to encourage convergent conversations and parametric changes; and (3) hybrid media, which incorporate combinations of different media, such as photographs, drawings or text, which are argued to allow a flexible exploration of the relations between different elements of the design solution.

These typologies demonstrate the various perspectives in which prototypes can be seen. However, more importantly, these different types indicate individual emphases in the use of prototypes in design practice. As artefacts, they focus on various design activities and serve different purposes along design processes. The findings from the literature reviewed above imply that designers devise different types of prototypes to facilitate specific outcomes at various stages in the design process, and that these different types have distinguished effects on how design solutions are perceived and collaboratively worked on. The reported findings, however, did not reveal just what effects the use of prototypes is aimed at. This raises the question as to how exactly and in what ways artefacts affect and facilitate design processes.

2.1.4 Effects of prototypes

Psychological effects

Arguing that "prototyping not only influences work outcomes, but also the way people feel about the work", Gerber and Carroll (2012, p. 18) observe the psychological experience of prototyping. In an eighteen-month ethnographic study conducted at a high-tech firm, they investigated how 35 members of the workforce felt when participating in low-fidelity prototyping. The authors report three features of the psychological experiences when prototyping: (1) prototyping allowed reframing failures as learning opportunities; (2) prototyping fostered a sense of forward progress; and (3) prototyping strengthened people's beliefs in their creative abilities. One way prototyping exerts this effect is by promoting control in situations of uncertainty, as Gerber and Carroll point out:

> When prototyping, practitioners break larger tasks into modest size tasks, allowing them to take frequent action. By taking frequent action on manageable tasks, practitioners experience small wins by observing their impact and attributing success to their actions (p. 3).

By understanding failure as necessary and beneficial within this process, this leads practitioners, according to Gerber and Carroll, to increase their confidence in their creative ability and motivation to act, despite the uncertainty of the design processes' outcomes. In a series of experiments with design students investigating the effects of parallel prototyping, Dow, Glassco, Kass, Schwarz, Schwartz and Klemmer (2010), support these findings by observing that "when people create multiple alternatives in parallel, they produce higher-quality, more diverse work and experience a greater increase in self-efficacy" (p. 18), while engaging in serial critiques about the prototypes produced resulted in more defensive postures (Dow et al., 2010).

Design fixation

Youmans (2011) reports, in a study conducted with 120 students on the effects of physical prototyping on design fixation, that the solutions were better and contained fewer fixations when designed in a physical prototyping environment instead of an environment without prototyping possibilities. He notes that design fixation is a robust phenomenon because information is being stored in the human brain via "associative networks of interconnected concepts in ways that make recently-activated concepts more likely to be retrieved" (p. 116). As the design process is complex and involves different cognitive abilities, he proposes that physical prototyping could be thought to reduce design fixation because it stores current ideas, thus reducing the mental workload and making room for critically reflecting these ideas. This observation is reminiscent of van der Lugt's (2005) category of 'storing sketches', where sketches seem to serve the same purpose. Additionally, Youmans investigated the performance of groups versus individuals and concludes that the performance and advantages of group work may depend largely on the state of the environment and especially emphasises the importance of physical prototyping environments. However, others, like Christensen and Schunn (2008), argue against the decreasing effect of physical prototypes on design fixation and propose the opposite. They observed that on the contrary, unsupported cognition and design processes supported by sketches "had more mental simulations than did cognition with the support of prototypes" (p. 342). Investigating their hypothesis that physical models lead to an increased design fixation, Viswanathan and Linsey (2009) conducted a controlled experiment, reporting that, contrary to the hypothesis, physical models can overcome gaps in designers' mental models and produce a greater number of functional design solutions.

There appears to be a fundamental disagreement when reflecting the effect of prototypes on design fixation. One possible way to shed light on this issue could be to observe the prototypes embedded in social interaction. When taking a closer look at how sharing individual ideas influenced the design process, Dow, Fortuna, Schwartz, Altringer, Schwartz and Klemmer (2011) observed that "when people produce and share multiple alternatives with peers, they explore more diverse ideas, integrate more of their partner's features, engage in more productive design conversations, and ultimately, create higher-quality work" (p. 8). The authors argue that single prototypes tend to focus design discussions on the refinement of a specific idea represented by the prototype. While this might be beneficial in some group communications, working on a single prototype not only fosters design fixation, but also encourages designers to over-invest in one specific idea. However, they observed that by having designers share multiple prototypes with other designers, and then collaboratively working on a shared prototype, the negative effects can be overcome and better outcomes yielded.

Iteration

In a laboratory experiment researching the difference between individuals conducting iterative testing and individuals prevented from iterating their design solution, Dow et al. (2009) report that "rapid iterators not only outperformed non-iterators, their self estimate of task performance significantly increased from before the design period to just before the task performance test" (p. 8). However, they argue that iteration does not lead to a divergent exploration of a variety of different concepts. Iteration, it seems, only affected the overall solution as an outcome of the design process.

Refinedness and complexity

In a study of two design engineering classes at Caltech, Yang and Epstein (2005) investigate the influence of the complexity of prototypes. They report that more time spent in the early stages of the prototyping process leads to a better design outcome. In addition, time invested in the early stages of the prototyping process is beneficial for the design solution. Accordingly, more time spent later during fabrication does not necessarily improve the design outcome. Leifer and Steinert (2011) endorse this claim, putting forward in a related study that "there is an inverse relationship between the refinedness of the prototype material and the size of the solution space opened up by the created conceptual alternatives" (p. 171).

Prototyping materials

Lawson (2006) suggests that the form that design is being represented in may potentially have great effect on the design process itself. Leifer and Steinert (2011) argue very much in the same way that "the choice of the prototype material or environment, directly influences the amount and degree of the generated alternatives" (p. 162). Edelman et al. (2009) present a study of a university's vehicle driving dynamics laboratory. They observe that "design thinking occurs in the presence of media, and the type of media conditions the kind of thoughts a design engineer has" (p. 397). Based upon the hypothesis that "rough sketches and prototypes yield paradigmatic changes in a model and high-resolution renderings and models yield parametric changes" Edelman and Currano (2011, p. 62) observe in design practice that 'ambiguous media' encourage divergent conversations, 'mathematised media' convergent conversations. Barbapour Chafi (2014) echoes this claim in a meta-study of the existing research regarding different kinds of embodiment used to externalise design solutions. She states that "sketching is considered an intelligence amplifier, while digital modelling is regarded as a creativity inhibitor" (p. 42). Viswanathan and Linsey (2010) even ask whether physical models, in general, are a "hindrance or help", as they might lead to design fixation. However, when looking at the advantages of physical prototyping, Barbapour Chafi (2014) argues that "in contrast to sketches, which can only be read through vision, the tangible nature of physical models enables the designer with multimodal interaction" (p. 38) and that their use might lead to "finding geometric relations that would otherwise be hidden in one representation" (p. 44). While the contrast between sketching and physical modelling may be a stark one, the effects of the specific types of material used seems to be more subtle but nonetheless influential. When developing a method to investigate designers' shape modification activities and applying it to the observation of modelling with clay, Wiegers, Dumitrescu, Song and Vergeest (2006) found that more than half of the time spent on the model was used to make modifications. In contrast, time invested in examining the models was only recorded on an average of 7 percent of the total time. This finding illustrates that the materials used when designing not only influence the form of the final design solution, but also the process of designing itself.

These observations seem to imply that the specific material of a prototype informs the conversation taking place within design activities. Whyte, Ewenstein, Hales and Tidd (2007) suggest distinguishing between 'frozen' materials, which are not available for change, and 'fluid' materials, which are dynamic in nature. They argue that the characteristics of the materials used set out "the tempo, beat, pace or rhythm for structuring the social relations" (p. 26). Hence, designers should, according to Whyte et al., be mindful about the pace and style of their interactions by carefully choosing the different types of visual materials when designing collaboratively. However, only a little is known about the specific characteristics of prototyping materials in design processes, especially in regard to the kinds of interaction they facilitate.

These findings demonstrate that the generation of design artefacts relates strongly to the outcomes of design processes. They also indicate that prototypes play an important role on a psychological level, closely linked to the social processes occurring during collaboration. As shown in the literature reviewed above, there are, however, different takes on just how prototypes and sketches inform design collaboration. For example, when looking at the concept of design fixation, it is not obvious at all whether prototypes foster or impede the divergent exploration of design ideas. Dow et al.'s (2011) observation regarding the sharing of prototypes leading to overcome design fixation points to the conclusion that it is necessary not to look at these effects as isolated events, but in conjunction with the social activities occurring simultaneously. Thus, the findings point to the question as to how artefacts and their generation correlate with the social aspects of collaborative design processes, and in particular the verbal and non-verbal interaction taking place in co-located design activities.

2.2 Artefacts and conversations

2.2.1 The conversational nature of design

Particularly in the early phases of the design process, which is characterised by informality and open-endedness, Catledge and Potts (1996) argue that social factors like organisational culture or effectiveness of group collaboration are equally important to succeeding, as are hard engineering methods. With new communication and collaboration technologies emerging, interest in designing as a social process of interaction, negotiation and discussion in interdisciplinary teams has increased (Brereton et al., 1996; Perry and Sanderson, 1998; Oak, 2011). However, when investigating the interrelations between artefacts and social interaction taking place in designing, one is well-advised to take first a closer look at the most dominant form of co-located design collaboration: design discussions.

It is often argued that linguistic aspects of design distract from the designer's 'real' work, and that claiming that language is an essential part of the production of a design object is against many of the beliefs designers hold (Fleming, 1998). However, it appears not to be clear just what exactly 'real' design work is supposed to be.

Others oppose this view as well. Ariff, Ozgur and Badke-Schaub (2013), for example, point out that verbalisation is critical in negotiating shared understanding in design processes. Bucciarelli (1994) supports this claim and emphasises that discussion amongst different stakeholders in design projects is of great importance when negotiating between different 'object worlds', "worlds of technical specializations; with their own dialects, systems of symbols, metaphors and models, instruments, and craft sensitivities" (Bucciarelli, 1998). The role of discussion in designing therefore is, according to Bucciarelli, "a process of achieving consensus among participants with different 'interests' in the design" (Bucciarelli, 1994, p. 159) which cannot be reconciled in object-world terms. An engineer and a chief financial officer, for example, would have a very different understanding and interpretation of a product prototype, which would arguably lead to misunderstandings and disputes without discussion. Yet, Bucciarelli argues that both of them need to "negotiate their differences and construct meaning through direct, and preferably face-to-face, exchange" (p. 159). Lloyd and Busby (2001) echo this claim by stating that "in design conversations a kind of 'world' is constructed with its own references, assumptions, symbol systems, and contributing experiences" (p. 68). They argue that, by closely analysing such conversations, the very construction of these 'worlds' can be examined and the underlying mechanisms by which language works in relation to a developing artefact can be understood. This thesis regards designing as a multifaceted activity, incorporating different modes of thought and forms of representation. From such a perspective, it is argued that verbal and non-verbal interaction between designers can be justifiably regarded as an integral part of designing.

2.2.2 Aspects of design conversations

Understanding the different aspects of design conversations is important when trying to gain deeper insight into how such interactions inform and are informed by artefacts. They can reveal qualities, good or bad, specific to artefact-facilitated design conversations. Research has looked into various dimensions of verbal interaction in design processes. In trying to understand how conversations around artefacts – as a major part of social interaction taking place in collaboration – inform design processes, different aspects have been investigated in the design research literature in more depth:

Disagreement

As an important aspect of collaboration, research has investigated how designers negotiate disagreement about the development of a design solution in design discussions. When looking at how people express their individual assessments in collaborative processes, Matthews and Heinemann (2012) observed that while agreement or acceptance was uttered in as most direct and minimal a way as possible, disagreements were expressed in a more complex or indirect form, often delayed by in-breaths or silences. Concluding from their observations, they suggest that "interaction is geared towards social solidarity" (p. 658). In a similar investigation, Oak (2013) reports how 'reported speech', quoting another person in a conversation, is used to deflect decision-making and deliver assessments. She argues that reported speech is being carefully used to express negative judgments to save other participants' positive self-image and public regard. One way of doing so, Oak observed, was to avoid naming specific features of what was opposed. Oak points out that reported speech is "selectively used by whoever is doing the reporting to strategically and competently perform the interaction at hand" (p. 52). So, while one might be expecting a straight forward feedback, people might be giving replies that are more complex in nature, and probably focus more on 'saving face' or avoiding giving an opinion. While there are famous examples of cultural differences in the importance of 'saving face' – for example, the Japanese concept of 'face', 'mentsu' – Oak analysed an architectural design meeting in the UK, indicating a more universally observable phenomenon.

These findings echo McDonnell's (2012) observation of how collaborating designers deal with disagreement to allow progression in the design process. When investigating how disagreement is being accommodated to ensure forward progress, McDonnell (2012, p. 61) highlights three conversational devices: (1) "signalling the propositional status of a conversational turn", (2) "explicitly acknowledging that there are design alternatives yet to be resolved by enumerating them", and (3) "marking off different solution concepts about which there is disagreement by naming (technicalising)". Thus, when analysing design discussions, looking at how participants cope with disagreement, provides valuable insight into how efficient and effective their collaborative work progresses. It might be argued, however, that to some extent such observations could be made in all kinds of conversations where a course of action is negotiated, not just specifically in design-related discussions.

Formality

Eckert, Stacey and Earl (2013) follow a similar line and argue that communication amongst designers and non-designers alike is often riddled with misunderstandings, flaws and difficulties. To better understand the reasons why those impediments occur, they suggest looking at the formality of the design process, the interactions between the participants, and the representations containing design information. Eckert et al. (2013) understand formality "as adherence to rules, or as strictness of entailment" (p. 92) and distinguish between implicit and explicit formality. The authors point out that "formality can be modulated in the mannerism of communication, the rhetoric employed, and how representations are constructed, to make communication more effective" (p. 91). They conclude in arguing that the rules and expectations according to which the different levels of formality are governed both create and restrict the possibilities of how designers plan and execute their designing activities. When analysing the path a design conversation follows, analysing the formality of talk might thus help to understand why certain design activities were executed and others were not. However, this raises the question as to whether there are formalities unique to design conversations or whether they can, to a certain extent, be found in all conversations as well.

Tentativeness

McDonnell (2009) argues that collaborative negotiation in designing activities leads to a sense of ownership and thus more effective collaboration. In a related investigation into collaborative negotiation, McDonnell (2012) focuses on how tentativeness supports constructive collaboration and looks more closely at the conversational strategies applied to accommodate disagreement. By analysing the spoken exchanges, she characterises an observed design session as 'fluid expert design practice'. As such, McDonnell reports the designers' discussion to move between the requirements and the design, between design context and use context, as well as between breadth and depth of the design solution. Tentativeness is identified as an important feature of discussion, as it provides different types of moves in the design process which are crucial for progression: projecting possibilities without signalling commitment, suggesting refinement of potential design details, and making acceptable backtracking, unravelling earlier design conjectures. Glock (2009) supports this observation and argues that "vague expressions perform important functions in conveying meaning which require context for an appropriate understanding" (p. 18). However, just how tentativeness relates to the sense of ownership is not obvious. For example, at first sight it seems that the notion of proposing a possible idea for a specific design without commitment and by making backtracking easy could inhibit an emotional and cognitive identification with the design solution. But tentativeness used as a conversational strategy employed by designers could help to disguise personal commitment to a specific idea and thus make the proposition more acceptable and even allow others to identify with it. Either way, tentativeness appears to possess great influence on the conduct of conversations, which needs to be addressed when analysing design discussions.

Evaluation

By analysing team communication sentence by sentence, Stempfle and Badke-Schaub (2002) take a closer look at the basic elements of thinking in design, especially the four basic cognitive operations of generation, exploration, comparison and selection. They observed two processes of how solution ideas were treated: process 1, where ideas are immediately evaluated, and process 2, where ideas were first analysed and then evaluated. Their observation showed that, while process 1 yielded considerable savings in time and cognitive effort, it was also more likely to produce errors when the complexity of the design problem increased. This observation suggests that what and when decisions are agreed upon during design conversations might be related to two specific qualities of talk the participants are engaged in, which could be designated as 'analytical-and-evaluative' or 'evaluative-only'. However, these observations do not give any clues as to when and why such qualities of talk might appear, and what factors might inform them. As one possible explanation, it could be hypothesised that the 'evaluative-only' process is used when time is more limited, as, according to Stempfle and Badke-Schaub (2002), it allows for significant "savings in time and cognitive effort". But the results were gathered in a laboratory setting with three teams developing a collaborative design solution over the duration of three hours. Thus, such an interpretation falls short of explaining the difference.

Sharing mental models

Casakin and Badke-Schaub (2013) investigated the role of mental models in collaborative design activities. Mental models, they argue, can be defined as "simplified representations of reality that serve for processing of new information, and acting in unknown situations with little mental effort" (p. 162). As such, they can enable understanding and predicting individual and team performance, as well as behaviour in problem-solving, and thus help to improve team communication. By analysing an architectural design meeting, Casakin and Badke-Schaub (2013) observe that when a certain degree of sharedness of mental models held by the individual participants is reached, less verbal communication is needed and a decline in the frequency of verbal utterances can be observed. Their results show that the participants spend most of their efforts at the beginning of the design session exchanging information concerned with the task. When analysing design conversations, these findings point to an observable quality of talk that is signified by a higher or lower degree of sharedness of mental models. It might be argued, however, that these findings might be related to the specific example of architectural meeting, between an architect and its client, chosen by the authors. For example, as one of them is not a trained designer or architect, the communication of their respective mental models will predominantly be accomplished by verbalising them. This might be quite different when two designers or architects meet, who are experienced in communicating their ideas in non-verbal, more visual and tangible ways.

The aspects of design conversations reviewed above indicate possible qualities of design discussions suggested by closely analysing the verbal-interaction taking place between designers. When looking at the interrelation between artefacts and social interaction, these aspects might play an important role. Since it is argued, however, that designing is a multi-modal activity, it seems necessary to take non-verbal interaction into account as well.

2.2.3 Non-verbal communication in design conversations

Conversations, especially in an explicitly visual and tactile domain like design, do not limit themselves to the spoken word, but also rely heavily on non-verbal communications. Knapp (1978) identifies seven different categories of non-verbal communication: (1) environmental factors, like lighting, smells, temperature or architectural style; (2) proxemics, the use and perception of one's social or personal space; (3) kinetics, like gestures, postures or body movements; (4) touching behaviour, the physical contact between people; (5) physical characteristics, like physique, height, hair or skin colour; (6) paralanguage, which comprises pitch, volume, intensity, and tempo; and (7) artefacts, which are in contact with people interacting, like perfume, lipstick or sunglasses.

Lloyd, Lawson and Scott (1995) put forward that "thought is always mediated", e.g. through words, signs, objects or gestures, representing different kinds of thinking. When designing, and particularly in design conversations, many different parallel lines of thought are being employed. Conducting a protocol study focusing on concurrent verbalisation during designing, Lloyd et al. observed a decrease of the verbal rate at various instances, indicating an engagement in abstract activities that were incompatible with verbalisation. Thus, Lloyd et al. argue against a "unitary notion of design' [...] the idea that designing is one 'thing'" (p. 258) and, in contrast, suggest that designing should be understood "as consisting of many interlocking and overlapping processes" (p. 239) which incorporate different modes of thought.

Likewise, tacit knowledge is commonly thought to influence design in a distinctive way (Mareis, 2012). It is often linked to characteristic design activities, like sketching or modelling, but also to activities like showing, presenting, mimicking and trying out. Mareis points out that: "What these attributes have in common is that they refer to non-verbal activities – meaning visual, aesthetic, haptic, performative, or motoric and gestural aspects – in and on which knowledge in design should manifest itself in a non-verbal manner" (p. 63). Glock (2009) echoes this perspective that in design discussions "participants often construct activities through simultaneous use of different kinds of semiotic practices in different media (such as language, gesture and drawing) which mutually elaborate each other" (p. 5). Below, two of the most important ways of non-verbal interaction in collaborative design processes – gestures and the use of interpersonal space – will be looked at in more detail.

Gestures

One distinguished form of non-verbal communication, especially in design conversations, is gestures. McNeill (2005) argues that: "Gesture is an integral component of language in this conception, not merely an accompaniment or ornament" (p. 20), and observes that about 90 percent of spoken utterances in 'descriptive discourse' are accompanied by gestures. He identifies two basic features: (1) they carry meaning, and (2) they are co-expressive with simultaneous speech. There is some neurological evidence to support the importance of gestures in conversations. Clark (2008) argues that certain kinds of thinking can only occur when hands actually move. With the discovery of the 'mirror neurons', investigations in the links between gestures and speech increased (Özyürek & Kelly, 2007). McNeill (2007) argues that "without gestures [...] the brain circuits required for language could not have evolved in the way they apparently have" (p. 31). He puts forward that:

> [W]hat was selected in human evolution is a capacity, not present in other primate brains, for the mirror neuron circuit to respond to one's own gestures as if they belonged to someone else (thus gesture is activated as part of social interaction, producing among other things the social dependence of gestures when the addressee is invisible—speaking on the phone, a blind person talking to another blind person—but not speaking into a tape recorder) (p. 31).

Cutica and Bucciarelli (2011) support this view and argue that gestures help speakers to organise their stream of thought.

Regarding the effects of gestures on collaborative design activities, Chu and Kito (2011) investigated the influence on co-thought gestures on spatial visualisation tasks using three control groups: a gesture-prohibited, a gesture-allowed, and a gesture-encouraged group. Their analysis showed that the gesture-encouraged group's performance was enhanced and they solved more problems than the other control groups. Chu and Kito suggest that gestures "enhance performance on spatial visualisation tasks by improving the internal computation of spatial transformations", and that indeed "hand movements play a key role in solving three-dimensional mental rotation problems" (p. 102). This claim is supported by Trafton, Trickett, Stitzlein, Saner, Schunn and Kirschenbaum (2006), who report that gestures accompany speech particularly frequently when spatial transformations are being described, and especially when it is difficult to describe spatial visualisation verbally (Hostetter, Alibali & Kita, 2007). In a related investigation, Mewburn (2009) analysed the use of gesture in architectural design discussions. She points to three key aspects in which gestures are used:

> [1] Explaining and describing architectural composition, [2] 'sticking' spoken meanings strategically to representations and [3] conveying the phenomenological experience of occupying architectural space – the passing of time, quality of light, texture and movement (p. 2).

These observations are limited to the role gestures seem to have in conveying spatial concepts. However, representing spatial information is only one function gestures seem to serve. Referring to earlier work by McNeill, Cassell and McCullough (1994), Ekman and Friesen (1972), Efron (1972), Kendon (1983) and Krauss, Chen and Gottesman (2000), Cutica and Bucciarelli (2011) propose three different categories of gestures:

(1) deictic gestures, which are indicative or pointing acts;
(2) representational gestures, which are referring to actions, characteristics, relationships, forms or movements, and can be either concrete (iconic gestures) or metaphoric gestures;
(3) beat gestures or motor gestures, which are rhythmic or repetitive hand movements that do not contain semantic content.

Hostetter and Alibali (2008) emphasise the importance of representational gestures, arguing that they arise from an embodied cognitive system and stem from spatial representations and mental images. They suggest that "gestures occur as the result of simulated action and perception, which are the bases of mental imagery and language production" (p. 511).

Endorsing the importance of gestures in this more general sense, especially in design activity, Leifer and Steinert (2011) report that in a study investigating human-computer interaction amongst designers, the imitation of body language significantly improved collaboration, and argue that it is necessary to incorporate not only the audio and the visual, but also gesturing in such systems. They do, however, not answer as to how exactly and in what ways gestures contributed to the collaborative process. Cutica and Bucciarelli (2011) give one possible explanation as to why gestures seem to contribute to better collaboration by reporting that "gestures favour the construction of a complete and articulated mental model of the discourse by the listener" (p. 173). Another explanation offered is that by using gestures, people reduce their cognitive workload and free up resources available for other tasks (Alibali and DiRusso, 1999). Gesturing has also been demonstrated to help focusing on perceptual and motor knowledge (Alibali, Kita & Young, 2000) and to increase the imagery content of conversations (Gyselinck & Tardieu, 1999).

The specific role of gestures in designing has also been investigated by Visser and Maher (2011). Identifying that this topic represents a relatively new interest in the field of design research, they point to the scarcity of research on gestures in designing. As the two main functions observed in collaborative design situations, Visser and Maher identify: (1) rendering of spatial and motion-related qualities of design objects, as well as embodying action sequences by mimicking simulation; and (2) organising interactions between different participants and functional design activities like generation, transformation and evaluation.

These findings point to the various ways in which gestures might contribute to the non-verbal interaction in design collaboration. But, compared to verbal interaction in design processes, only a little is yet understood about the role of non-verbal gestures. Identifying this lack in the literature, Mewburn (2009) hypothesises that this might be due to the difficulty of studying the meaning of gestures, as they are "spontaneous and provisional". However, further complicating their interpretation is the fact that gestures are always embedded within a spatial context. By its very use, the physical space in which gestures are performed represents its own form of non-verbal interaction.

Use of interpersonal space

Lloyd (2009) argues that "the space between people creates and defines the social dynamics of our interactions with others" (p. 297). He suggests that the use of the space between participants in a conversation should be understood as an important aspect of non-verbal communication in face-to-face meetings. Likening people's behaviour in space to a language that can be read and understood, Lawson (2001) emphasises:

> We use the language of space [...] for many purposes. Through it we can express both our individuality and our solidarity with others. We can indicate our values and lifestyles, allegiances and dislikes. [...] We can communicate our willingness or otherwise to be approached, interrupted, greeted and engaged in social intercourse (p. 2).

Earlier research has demonstrated that people define the space around their body as an area into which others cannot intrude without prompting discomfort or withdrawal (Hayduk, 1978). Intruding into such an individual space can evoke the perception of psychological or biological threat to one's integrity (Horowitz et al., 1964). Lloyd (2009) argues that, consequentially, emotional and motivational factors can have an important influence on the use of interpersonal space. Studying design students at Stanford University, Leifer and Steinert (2011) observe that "the proximity between the people is key for change as it allows transmitting and thus learning knowledge through a multitude of channels" (p. 171). In their investigation, they posit that "creating proximity can facilitate change and its prerequisite, collaboration" (p. 168), illustrating the importance of interpersonal space in collaborative design activities. They do, however, leave it open to speculation as to how exactly proximity facilitates collaboration.

Answers might be found in the domains of anthropology and psychology, where an entire field of scientific investigation has dedicated itself to the research of 'proxemics' – the study of how people make use of the physical space in the interaction with others. In proxemic studies, space is widely being classified into four categories (Prabhu, 2010): (1) public space, which defines an area of around 12 ft to 25 ft around an individual; (2) social space, which comprises an area of 4 ft to 12 ft; (3) personal space, which is about 18 inches to 4 ft; and (4) intimate space, which is an area up to 18 inches. Within those spaces, Hall (1978) suggests that eight different variables of proxemic behaviour are observable:

(1) Postural-sex identifiers (the influence of postural status and sex identity with reference to space)
(2) Sociofugal-sociopetal axis (the position of face and shoulders in relation to another person)
(3) Kinaesthetic factor (different touching distances between people)
(4) Touch code (the different kinds of touch between people)
(5) Visual code (the amount of eye contact)
(6) Voice loudness (the volume of a voice in relation to the space)
(7) Thermal code (the transmission of body heat)
(8) Olfactory code (the presence and intensity of breath and body odours)

Prabhu (2010) explains that while not all of these factors are equal in their complexity or magnitude, a careful observation of them during social interaction allows the researcher to "provide significant details regarding the non-verbal aspect of communication" (p. 11). When observing proxemic behaviour, Hall (1963) points to an important aspect by underlining that "proxemic patterns, once learned, are maintained largely out of conscious awareness and thus have to be investigated without resort to probing the conscious minds of one's subjects" (p. 1003). While this may necessitate a more intricate approach to observing and analysing social interactions than when being able to question people directly about their actions, it also means that subjects are less able to manipulate their behaviour. Thus, the data gathered and analysed in such investigations provides a candid and undistorted look at interactions as they are being shaped consciously and subconsciously. Hall emphasises that "the very absence of conscious distortion is one of the principal reasons for investigating behaviour on this level" (p. 1003).

In analysing proxemic behaviour, the researcher has to be aware of the fact that this behaviour is a property that was learned and adopted within specific cultural contexts by the observed. Thus, individual differences in the use of interpersonal space have to be accounted for. Hall (1963), for example, recounts the experience of alienation of a Chinese person in the United States "when he was faced directly and seated on the opposite side of a desk, for this was defined as being on trial" (p. 1006). Another issue in analysing proxemic behaviour is the systematic and objective description of what is being observed. To that end, Hall proposes a notation system which is designed to facilitate the recording of all eight variables of behaviour mentioned above. However, as Hall annotates himself, this system is only aimed at analysing "observations of a very limited nature" (p. 1022).

As shown above, the existing literature underlines the importance of non-verbal interactions, especially of gestures and the use of interpersonal space, in design discussions. Its findings give valuable insight into crucial aspects that influence design collaboration at a more intangible level of communication. However, they look at proxemics in a rather general perspective and are not specifically related to collaborative design processes at all. Thus, they raise the question as to how the aspects observed are linked to the actual generation of physical design solutions and how they relate to other dimensions of the design process. When collaboratively designing, verbal and non-verbal interaction seldom takes place without the use of prototypes – albeit as a crude model hardly recognisable as a design solution, or as an elaborately designed concept model. This thesis argues that, in order to better understand collaborative design processes, not only the social interactions need to be investigated, but also the physical dimensions of designing, especially the use of prototypes.

2.2.4 Artefacts in design conversations

The literature documented above shows the importance and the individual aspects of both prototyping and the verbal and non-verbal interaction taking place in collaborative design processes. However, when recognising designing as a social as well as a prototyping activity, it is important to understand the relations between these two domains in depth. Despite their crucial role in designing, the existing literature does not tell us much about their specific relations.

Luck (2007) argues that only "[i]n conversation and action, a design is realised" (p. 29), underlining the importance of considering both discussing and producing an artefact as one activity called 'designing'. According to Perry and Sanderson (1998), when designing, visual representations provide "a common basis through which people with different skills and perspectives could gain a common understanding of the problems discussed" (p. 283). The way this is accomplished, Perry and Sanderson observe, is interdependent: on the one hand, artefacts serve as a resource for discussion, while they are, on the other hand, being generated and modified through these conversations. Bucciarelli (2002) even claims that we should be "extending the scope of language to include artefacts" (p. 219). Emphasising the communicative aspect of artefacts, Ewenstein and Whyte (2007) point out that "the communicative and interactive properties of visual representations constitute them as central elements of knowledge work" (p. 81).

In an observation on a graphic design project, Fleming (1998) reports the occurrence of two different kinds of talk: 'object-laden talk' and 'language-laden talk'. In the former, the conversation revolves around a design object, or as Fleming puts it: "the object leads and language follows" (p. 46). The use of language is relatively sparse and it relies heavily on the object. In the latter, the existence of a specific design object is assumed and its possibilities explored. This kind of talk includes "instances of narration, argument, and application" (p. 46) and is relatively independent of the material object. Fleming proposes that these two types of design conversations represent poles of a continuum with three different stages between them: indexing, constituting and elaborating. By constantly switching between those stages, he argues, designers are able to satisfy the conflicting demands of solidifying ideas and moving projects forward, on the one hand, and, on the other, remaining sensitive to the social situation and adapt in a flexible manner to it.

The importance of artefacts in design conversations is also echoed in Stacey and Eckert (2003), who emphasise that:

> [W]hat the senders of communications need to achieve is to supply design elements, evaluations and objectives, and impose the correct constraints on their colleagues' designing activities, to ensure that they develop shared models in appropriate ways, or that the other models they produce are consistent with the senders' own (p. 165).

In an earlier study, Eckert and Stacey (2000) observed that "many characteristics of designs cannot easily be expressed in any absolute terms without reference to examples and variations from them" (p. 538).

2.2.5 Qualities of artefact-facilitated conversations

There appears to be a close relation between the artefacts produced in design activities and the verbal and non-verbal interaction occurring over them. Some even observe a more fundamental connection and argue that "from an evolutionary viewpoint, there is an entanglement between speech and tools whose roots go back to a bipolar technicity found in many vertebrates" (Radford, 2014, p. 406). It has also been observed that while artefacts are "a resource for discussion, [...] they were also generated and modified through these discussions" (Perry & Sanderson, 1998, p. 285). However, despite this important connection, there is only sparse literature on what qualities artefact-facilitated conversations possess:

Factoring in tacit knowledge

Observing design discussions supported by the use of artefacts in an early stage of a building's design, Luck (2007) concludes that "users' understanding of the design was developed in the conversations around the use of artefacts, as well as the knowledge that is embedded in the artefacts themselves" (p. 28). This suggests that one possible quality of conversations evolving around artefacts is that they foster mutual understanding by making knowledge tacitly embodied in objects available and negotiable. Luck emphasises this interpretation by advancing that "it was only through design conversations [..]., that the artefacts of design became more meaningful to the users" (p.36).

Flexible focus

Another quality that may be associated with artefact-facilitated conversations is implicitly being put forward in Whyte et al.'s (2007) observation of the use of 'fluid' and 'frozen' artefacts in design conversations. They argue that in design practice many different kinds of visual materials are treated as either "fluid, when they are altered through the unfolding practice; and frozen, where they are referred to and talked about, but themselves remain unchanged" (p. 21). By using design artefacts in that way, Whyte et al. observe, designers are able to set the "tempo, beat, pace, or rhythm for structuring the social relations for delivery", as well as "the rate and direction of knowledge evolution" (p. 26). Thus, by switching between frozen and fluid materials, artefact-supported conversations seem to possess a flexible focus that allows designers to change the direction and speed of the design development in order to stay on track and negotiate different interests of individual parties. Hindmarsh and Heat (2000) support this observation by stating that "object-focused discussions 'knit together' disparate tasks and work in the organization, providing a momentary hub through which divisions of labour and courses of actions are managed and coordinated" (p. 554).

Coping with boundaries

Carlile (2002) identifies three characteristics of effective boundary objects: (1) establishing a shared syntax or language to represent knowledge; (2) providing a concrete means to specify and learn about differences; and (3) facilitating joint transformation of knowledge. These features are crucial aspects in successful design conversations. In an ethnographic study, Holzer (2012) investigated the role artefacts played as mediators in talk, observing that "[t]he boundary objects – the stage-gate objects and the designed prototype – enabled team members to maintain the boundaries between social worlds while allowing them to cross the frontiers in practice-related structures", and that "[w]hile new meanings were constructed, the object developed, resulting in an emergent meaning construction process – and a new technological innovation" (p. 58). Thus, these findings suggest that an important quality of design conversations facilitated by artefacts is that they help participants cope with boundaries between 'object worlds' by providing a shared language to exchange and jointly transform knowledge.

2.3 Summary

This chapter has shown that there is a consensus within the design research community regarding the distinctive roles artefacts and social interaction play in designerly ways of solving problems. It also illustrates that while the concept of the designer as lone genius still prevails in the public perception of the profession, it has very much deserted professional design practice, as ever more complex tasks require incorporating the expertise from many different domains. Today, to design implies to socially interact. The predominant form of social interaction in collaborative design processes is arguably face-to-face meetings. In such meetings, the progress of the design solutions developed is negotiated by verbal and non-verbal interaction amongst participants.

While the importance of artefacts, and prototypes in particular, in the design process has been recognised for a long time now, just how they inform and are informed by this interaction process is still very much unknown. This chapter has summarised the research on the psychological effects of the many variations of prototyping, as well as their influence on design outcomes. Prototypes, for example, seem to foster a sense of progress in the design process, reframe failures as learnings, or strengthen people's belief in their own creativity. They also play a crucial role in design fixation, although it is not quite clear what, and they seem to inform design processes by their very existence. Yet, very little is known about the interdependent role of prototypes in face-to-face meetings. In the past decade, conversational aspects of design meetings have received increased attention. The relations between both verbal and non-verbal interactions and prototypes, however, remains very much an under-researched area.

It appears that while the importance of these relations becomes more and more evident, ever more questions arise from reflecting the findings of the existing research. For example, just how prototypes inform the verbal and non-verbal interaction between designers, is still an unanswered question. Furthermore, it has been shown that the material of prototypes informs design processes, but what role exactly does it play in collaborative design processes and their respective social interactions? And how can we investigate these roles and relations? Thus, in the next chapter, this thesis will look at which methodological approach and which methods of design research may enable a better understanding of these relations and seem appropriate to answer these kinds of questions.

3

3 Methods and methodology of investigating design processes

The previous chapter has proposed possible directions and guiding questions for this thesis's research. This chapter aims to provide the methodological framework for systematic research, suitable to answer the questions posed and allowing for subsequent research in similar contexts to gain similar results. Design research draws upon the methodological approaches from various disciplines. This chapter will first briefly digress to review the methodological background and discourse which the research design of this thesis has to be mindful of. It then critically reviews the different methods that propose themselves for answering the research questions posed, and discusses their individual advantages and shortcomings.

3.1 Methodology

3.1.1 Researching design

Cross (1999) states the aim of design research: "Our concern in design research has to be the development, articulation and communication of design knowledge", but immediately afterwards continues by asking "where do we look for this knowledge?" (p. 5). Herbert Simon's (1969) much-referred definition of design as a process of devising "courses of action aimed at changing existing situations into preferred ones" (p. 112) gives a clue to the broad spectrum. Cross (1999) suggests three main categories of design research: (1) design epistemology (the study of designerly ways of knowing); (2) design praxiology (the study of the practices and processes of design); and (3) design phenomenology (the study of the form and configuration of artefacts). As to how these should be investigated, he argues that design researchers should draw upon the methods and methodologies of other fields where appropriate, but only "while building our own intellectual culture, acceptable and defensible in the world on its own terms" (p. 7). Buchanan (2001) emphasises Cross's point of view by stating that design research "suffers many misunderstandings [...] One of these misunderstandings in the design community is a tendency to think that research means a single kind of activity" (p. 17). Seago and Dunne (1999) ask whether design research should adopt and adapt methodologies that were developed in and for other academic disciplines at all, or whether they should develop their own methodologies recognising "the distinctive quality of discovery in art and design" (p. 11). This led to a search for new methodological research strategies specific to design research (Seago & Dunne, 1999; Buchanan, 2001) which persists today, and in which tradition this thesis understands itself, too.

3.1.2 Design as a social and an engineering science

Two of the domains that are relevant to the field of design, pointed out by Friedman (2003), are the social sciences and the engineering sciences. As this thesis investigates designing as prototyping and social activity, the research traditions of these two domains are relevant for its research design. They, however, not only represent different scientific mindsets, but also are engaged in so-called 'paradigm wars' (Robson, 2002). This dispute can be discerned in design research as well: "These two scholars [Herbert Simon and Donald Schön] have been the most influential in our field, representing positivist and constructivist philosophies, respectively. Simon's positivism leads to a view of design as 'rational problem solving' and Schön's leads to a view of design as 'reflective practice' (Cross, 1999, p. 10). Robson (2002) claims that: "Essentially, positivists look for the existence of a constant relationship between events [...] However, when people are the focus of study [...] 'constant conjunction' in a strict sense is so rare as to be virtually non-existent" (p. 21). Thus, he argues to approach studies involving human behaviour from a realist's point of view, which "provides a model of scientific explanation which avoids both positivism and relativism" (p. 29), and which holds true that "the task of science is to invent theories to explain the real world, and to test these theories by rational criteria" (p. 32). The realist approach, Robson (2002) proposes, advocates using flexible research designs using quantitative and qualitative methods.

3.1.3 From observed practice to observable practices

To adopt a pragmatic, realist's stance, this thesis follows an open approach to various quantitative and qualitative research methods while remaining mindful of the limitations and biases of their individual epistemological justifications. The research journey undertaken in the course of this thesis can, in a nutshell, be described as moving from observing design activities in practice to focusing on observable practices in designing. The study first sets out to investigate what practices could be discerned in Swiss design firms. Based upon the findings and insights gained, a more controlled approach was used. This approach was chosen in order to retain the research's validity for design practice and design theory, as well as to improve the construct validity of the methodological approach.

3.2 Methods

Regarding design research methods, Faste and Faste (2012) point out that "the term 'design research' has become part of the common vernacular in the field of design and is increasingly used to describe a myriad of possible approaches, perspectives, philosophies and methods" (p. 1). Laurel (2003) lists nine different kinds of design research methodologies: (1) experimental, (2) qualitative, (3) quantitative, (4) speculative, (5) experiential, (6) performative, (7) discovery-led/poetic, (8) formal/structural, and (9) procedural. This illustrates not only the broad spectrum of methodologies and methods available to design researchers, but also the blurring of the borders, where it becomes rather opaque as to what methods meet the criteria of scientific inquiry. It also indicates the necessity to focus. Thus, this thesis places its priority on design methods that have proven themselves to be of value in researching the social interactions in collaborative design processes and in discerning designerly ways of knowing. The methods relevant to this thesis are critically reviewed below.

3.2.1 Current design research methods

According to Cross (1992), as a possible start of the research in design thinking, Marples's (1960) pioneering article studying 'Decisions of Engineering Design' could be seen as an eminent marker. Since then, a steady growth in the body of research work and methods applied can be recorded. As some of the most frequently used, Cross (2006) points out five methods: (1) case studies and observations; (2) interviews with designers; (3) protocol studies; (4) reflection and theorising; and (5) simulation trials. It seems worthwhile to look at some of the most relevant methods for this thesis in more detail.

Case studies

In his early, seminal text exploring the social dimensions of designing, Bucciarelli (1994) used the method of case studies to investigate three design projects in depth. Case studies are especially appropriate to investigate 'how' and 'why' questions concerning particular contemporary phenomena in context, where the researcher has little or no control over the subject investigated (Yin, 1994). Multiple-case studies allow for a replication of initial experiments, building upon previous experiments, or completing a study by focusing on a specific area not covered yet, which allows for greater analytical generalisation (Robson, 2002). According to Yin (1994), evidence in case studies may come from six sources: (1) documentation; (2) archival records; (3) interviews; (4) direct observations; (5) participant-observation; and (6) physical artefacts. A major issue when using case studies is how to achieve validity in case study research. Yin (1994) proposes four design tests: (1) construct validity; (2) internal validity; (3) external validity; and (4) reliability. Construct validity may be achieved by using multiple sources of evidence, by establishing a chain of evidence, and by having informants reviewing a draft of the case study report. Internal validity may be gained by pattern-matching, explanation-building, and performing time-series analysis. For external validity, Yin (1994) proposes to use a replication logic in multiple-case studies. In order to establish reliability, he suggests that case study protocols should be used and a case study data base developed.

However, the case study method has its shortcomings. Miles (1979, p. 600) claims that case study "research on organisations cannot be expected to transcend story-telling." Campbell and Stanley (1966) put it a little more harshly by stating that "Such studies have such a total absence of control as to be of almost no scientific value. [...] Any appearance of absolute knowledge, or intrinsic knowledge about singular isolated objects, is found to be illusory upon analysis" (p. 6). The main objections behind these criticisms are, as Flyvbjerg (2006) points out: (1) the prioritisation of context-independent over context-dependent knowledge; (2) the lack of generalisability of knowledge from a single case study; (3) case studies are suitable for generating hypotheses, but not for testing them; (4) their inherent tendency towards verification, i.e. their tendency to confirm the researcher's hypotheses; and (5) the difficulty developing general theories based upon specific case studies.

For example, Leitner, Innella and Yauner's (2013) study investigating the design process in a single case study left the researchers, according to their own account, to admit that all that was "left in our mind was doubt" (p. 512). Gathering data from interviews and the analysis of artefacts produced over a period of three weeks, the authors tried to identify a designer's process employed to a given design brief, but only found that the nature of the presentation seemed to have an effect on the client's appreciation of the design work. One possible reason for this perceived failure to observe the employed process properly might be found in the limited number of data sources. No direct observation of the actual design process, for example, was conducted, which could cross-reference statements from the interviews. Furthermore, when employing a single case study, time can be a crucial factor and in this case a handful of interviews conducted over the duration of three weeks might have been too little to actually observe the phenomenon addressed in this study. In practice, gaining access to designers willing to invest the amount of time and to provide the various data sources needed is a major hindrance of the case study method. This was experienced while conducting the first case studies in the earlier part of this thesis's research.

Observation

Observation is often used in case studies to obtain relevant data. Robson (2002) distinguishes between two polar extremes when considering direct observation as research method: 'participant observation', which represents a qualitative approach originated primarily in the field of anthropology, and 'structured observation', a quantitative approach used in a variety of different fields. "Participant observation", Robson reports "is a widely used method in flexible designs, particularly those which follow an ethnographic approach" (p. 310). As a major advantage, he emphasises the method's directness, in the sense that researchers do not need to ask people about their views, opinions or attitudes, but can instead watch their actions and listen to their talk. Agnew and Pyke (1982) articulate this advantage aptly "on a questionnaire we only have to move the pencil a few inches to shift our scores from being a bigot to being a humanitarian. We don't have to move our heavy-weight behaviour at all" (p. 129).

However, Robson (2002) also points to the drawbacks of direct observation. He emphasises the major issue of "the extent to which an observer affects the situation under observation" (p. 311). Commonly, two counterarguments are being put forward to address this problem. On the one hand, observation might be conducted in a way that keeps the observed in oblivion about the observation, and, on the other hand, they become accustomed to the presence of the observer in such a way that it does not affect their behaviour. However, the logical problem with these justifications is that the researcher cannot be sure of "what the behaviour would have been like if it hadn't been observed" (p. 311). Another issue is the time being consumed by observational studies. Classical participant-observation, derived from social anthropology, requires the researcher to immerse himself in a 'tribe' for two to three years. Robson points to the trend of 'condensed field experience' and more structured approaches to observation, which reduce the time needed to conduct the study. However, these require increased time investments in preparation of the actual observation.

Artefact analysis

Analysing the artefacts used and produced in practice is another important method of gathering data in case studies. Design objects can reveal a lot about what designers think and what tacit knowledge they possess. Cross (1999) observes that "design knowledge resides in products themselves: in the forms and materials and finishes which embody design attributes" (p. 6). Norum (2008) states the aim and value of artefact analysis more explicitly:

> Artefacts become data through the questions posed about them and the meanings assigned to them by the researcher. [...] In the process of analysis, we are asking the data to tell us something. An artefact has a story to tell about the person who made it, how it was used, who used it, and the beliefs and values associated with it (p. 23).

She identifies six different approaches to analysis that can be employed to question artefacts: (1) content analysis, (2) discourse analysis, (3) document analysis, (4) historical analysis, (5) narrative analysis, and (6) semiotic analysis. However, she also points to a possible shortcoming of artefact analysis: "There is no one right way to analyse artefacts. A wide range of disciplines informs the analysis of artefacts, including anthropology, archaeology, art history, history, human geography, ethnography, and sociology" (p. 23). There is no universally agreed way to analyse artefacts, which makes it more vulnerable to subjective interpretation of the researcher.

Expert interviews

One of the most traditional research methods is interviewing experts in the field. In design research, these usually focus on designers who have achieved some degree of expertise or well-established practice. Cross (2006) notes that, in the past, such interviews have aimed mainly to record the designers' own reflections about their processes and procedures in an unstructured way. Lawson (1994), as well as Cross and Clayburn Cross (1996), are examples of expert interviews in design research. The shortcomings of this method seem mostly in the way it relies on the interviewees' personal and subjective thoughts about their design practice. This reliance does not allow for an objective representation of design processes and procedure, but instead records the possibly idealised view of how designing should or could be performed. Experts were interviewed at the very beginning of the research for this thesis. While they did provide valuable first insights into the opinions and thoughts of the practising designers, they quickly proved to be a means not suited to investigate the emerging research question in more depth.

Protocol analysis

The 1994 Delft protocols workshop marked "something of a landmark in design thinking research" (McDonnell & Lloyd, 2009, p. 1). Having filmed designers at Xerox PARC solving design problems, this workshop focused on a specific research method, the protocol analysis. The basic assumption behind protocol analysis is that participants can be instructed to verbalise their thoughts in a manner that does not alter the sequence of thoughts mediating the completion of a task. Today, the method has become a primary tool for design researchers (Sarkar & Chakrabarti, 2013). However, for its focus on verbalisation, protocol analysis has been critiqued (Jiang & Yen, 2009). As Schön (1983) pointed out, the 'language of design' constitutes itself through tightly connected verbal and non-verbal elements. Some even suggest that "visual thinking is more crucial than symbolic thinking in designing processes" (Jiang & Yen, 2009, p. 1).

Protocol studies may be a well-established research method of design thinking and continues to contribute much to the field, but its specific drawbacks have to be considered when being employed. Goldschmidt (2014) names the most important: (1) protocol analysis only offers a partial picture of the thinking processes by relying on concurrent verbalisation; (2) it is hard to discern the units of analysis as they are often incomplete or not coherent; (3) reaching inter-coder reliability is very laborious, as, for example, verbalisations are often ambiguous, and thus interpreted differently by individual coders. Goldschmidt notes that it is well suited when looking at processes aimed at solving well-defined problems, but less so when investigating processes aimed at solving ill-defined problems: for example, design tasks. Furthermore, when reflecting on the outcomes of the 1994 Delft protocols workshop, Goldschmidt concludes that "among the most important lessons learned from this concentrated effort was that protocol analysis is not well suited for long episodes" (p. 37).

Its focus on concurrent verbalisation limits the protocol analysis's perspective on collaborative design processes rather severely. This thesis aims to answer the research question of *how different types of prototypes contribute to collaborative design processes, particularly the 'quality' of verbal and non-verbal interaction.* Although protocol analysis offers an intriguing means to gain insight into design activities, especially its implicit neglect of the non-verbal dimension of design, collaboration appears to be too limiting for this research.

Others have addressed these limitations as well. In the decade after the Delft protocols workshop, McDonnell and Lloyd (2009) observe a tendency of research into design thinking to broaden the scope of what was regarded as design activity. Increasingly, they point out, "social aspects of design thinking were being emphasised; one trend was towards paying attention to the way that designing occurs between people trying to reach a common goal, rather than on individual design problem solving" (p. 2). Accordingly, McDonnell and Lloyd report that a "wide variety of approaches used to look at designing in context [...]: interaction analysis, computational linguistics, viewpoint methodologies, semiotics, ethnography, functional linguistics, cognitive ethnography, and discourse analysis" (p. 2). This tendency indicates the need and search of design researchers for new research methodologies that suit the more social focus of their research inquiries better than protocol studies do.

Linkography

Building upon the traditional protocol analysis as well, but trying to gain a deeper understanding of the design process than what could be drawn from protocol studies, Goldschmidt (2014) developed a new methodology called 'linkography'. Essentially, it allows one to "notate design moves and the links among them" (p. 53) in a kind of modified matrix representation. This form of graphic notation, called a 'linkograph', was chosen by Goldschmidt, as it is better suited to "emphasize the idea of links as nodes rather than connecting lines" (p. 53).

It was first presented in 1990, but continually developed further to its present state. In its fundamental orientation, the methodology aims at investigating how the convergent and divergent modes of design thinking lead up to a design synthesis. It does so by making the links between different design moves visible. Design moves are defined as "brief acts of thinking, lasting around seven seconds" (p. 47). Taken together and viewed as a sequence of moves, they constitute the design process. As sequences, these moves form a continuum or pattern of links. As links are being defined depending on the contents of each individual design move, discerning them takes practice and a good grasp of the discipline as well as the specific design episode. Goldschmidt (2014) emphasises that: "Deciding whether two moves are linked is done by using common sense under the condition of good acquaintance with the discipline and with the design episode in question" (p. 47). The methodology differentiates between three types of moves: (1) orphan moves, (2) unidirectional moves, and (3) bidirectional moves. A special class of moves is being identified as 'critical moves'. These are characterised as design moves with particularly numerous links. Orphan moves, as counterpart to critical moves, do not have any links. Typically, they represent thoughts and ideas that are not followed up. Goldschmidt (2014) notes that orphan moves seem to occur more frequent when designers are novices, as experienced designers may be able "to anticipate the implications of their moves for longer stretches of future probable moves" (p. 57). Unidirectional moves are only linked to either a previous or a prospective design move. They imply that the designer had been reflecting on what was discussed or developed up to the instant of the move, or that the focus was on new thoughts not connected to what was negotiated up to this point. Bidirectional moves have both links to both previous and prospective moves. Thus, they seem to take up what had been proposed in previous design moves, but also bring in new ideas into the design process. According to Goldschmidt, in a typical design episode, close to two-thirds of all design moves tend to be bidirectional. When experienced designers are involved, the average can be a little higher.

The methodology also identifies different link patterns. 'Chunks' are being characterised as distinctly discernible triangles of links, usually comprising twelve to twenty-four design moves. Typically, they represent "a cross-examination of relevant properties, related questions, and possible implications of a design issue" (Goldschmidt, 2014, p. 63). A 'web' is the formation of relatively few design moves with many links between them. This link pattern is the record of "a brief and intensive passage of a few moves in which a certain issue is very thoroughly inspected and its aspects are woven together to make sure they are in agreement with one another" (p. 65). 'Sawtooth tracks' are being built when each design move only links to the preceding one. It is thought that they occur when "the thinking at that point is very linear – one thing leads to the next, and each move reacts to what was just said or done, without a more holistic view" (p. 65). Another characteristic of links is the link span. Long link spans imply the connection of design moves over a longer period of time, meaning minutes: in some extreme cases, hours. The assumption is that, due to the limitation of the working memory, design moves connecting over a longer time are being deemed important by the designers.

Overall, the linkography, provides a very valuable and powerful tool to unveil design processes. It allows one to look in-depth at how they unfold in their particular moves. With classifying individual design moves as well as patterns, researchers can gain a better understanding not only of the individual segments of the design process, but also when and how particularly important ideas seem to emerge. However, it is somewhat detached from the physical activity taking place in design processes. The design moves are elicited mainly based upon the verbal interaction between designers. But there are more dimensions to the interaction in collaborative design processes. While the method does not exclude non-verbal interactions as design moves per se, it does not provide a structured way to observe and categorise non-verbal interactions as design moves, nor does it offer a possibility to distinguish the nature of individual design moves.

Charting design processes

Visualising design processes and aspects of designing is not a new attempt. In the Delft protocols workshop, for example, different approaches were taken to that end. Goldschmidt's (1996) linkographs, showing how the individual moves appear in sequence and how they are linked to each other (Figure 1), represent only one route inspired by the Delft protocols workshop.

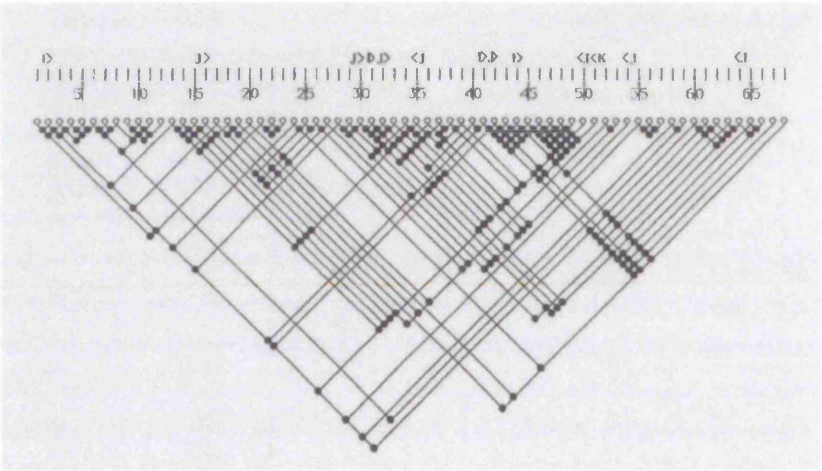


Figure 1: Goldschmidt's (1996) linkograph, visually representing the linkage between individual 'design moves'.

Radcliffe (1996) followed the spatial focus of the observed team's activities. He plotted the instances where the team was focusing on individual 'work loci' along the timeline, recording when they were working on the whiteboard, the artefact, sketches, and documents (Figure 2).

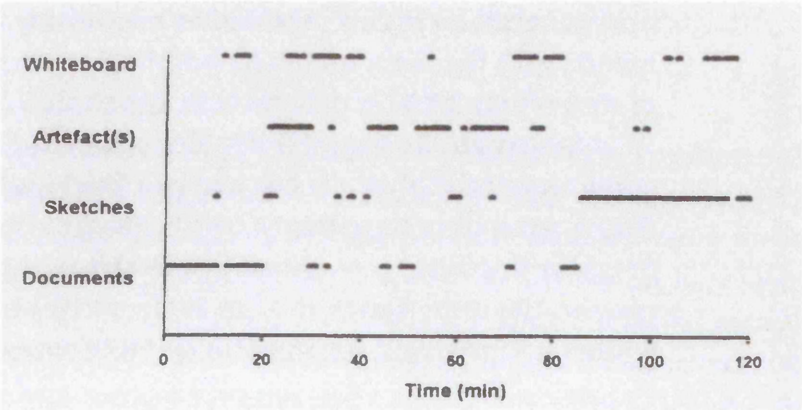


Figure 2: Radcliffe (1996) recording the different 'work loci' of the observed team's activities along a timeline.

Cross (2006, p. 70) reports Günther, Frankenberger and Auer's (1996) study (Figure 3), which charted protocol statements along a timeline, assigning each statement to one of three categories ('clarifying the task', 'searching for concepts', 'fixing the concept').

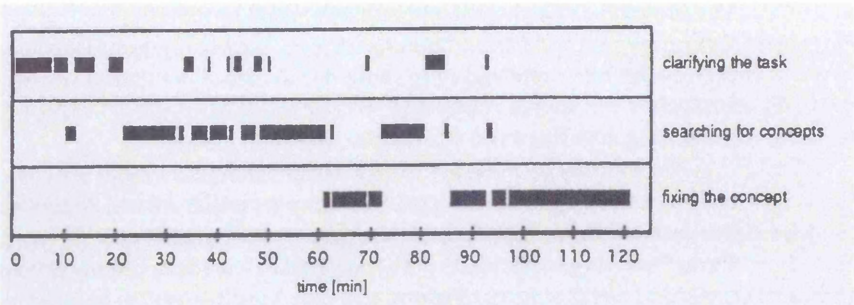


Figure 3: Günther et al. (1996) plotting protocol statements along a timeline assigning each statement to one of three categories.

In a similar attempt, Mazijoglou, Scrivener and Clark (1996) recorded the verbal statements, or the 'discourse production', of the team members (Figure 4). The statements were categorised in one of six aspects of the discourse (problem, solution, constraint, require, inform, and process).

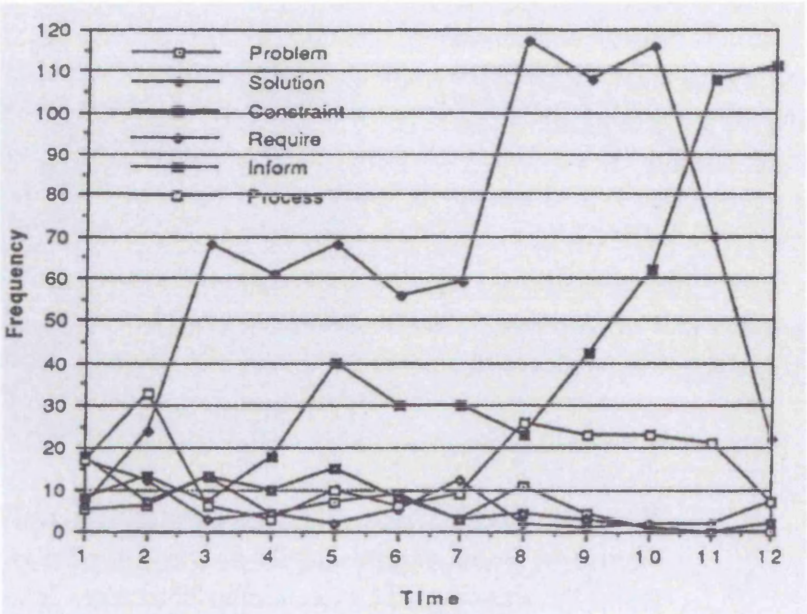


Figure 4: Mazijoglou et al. (1996) study recording the number of verbal statements and categorising them into six different aspects of the discourse.

All of these attempts to visually analyse design processes are valuable tools for design researchers. However, they still offer only a partialised view, not suitable to answer this thesis's research question, addressing the role of different types of prototypes in collaborative design processes.

Experiments and simulation trials

Robson (2002) labels experiments as "the prime example of a fixed research design" (p. 110). An experiment is a precise, focused research tool and requires a large amount of preparation as well as an exact understanding of how the research is going to be performed. Employed outside of a laboratory, this often places significant barriers to their effective use. Particularly when considering randomised controlled trials as the 'gold standard' in performing experiments, their contribution to the investigation of social aspects is subject of controversy (Robson, 2002). However, controlled experiments have been used in design research successfully (for example, Kokotovich & Purcell, 2007; Dow et al., 2009; Dow et al., 2010; Dow et al., 2011; Cash, Hicks & Culley, 2013). In fact, Cash et al. (2013) report that in 2011 one-quarter of the articles published in the peer-reviewed journals 'Design Studies' and 'Journal of Engineering Design' used experimental studies. Investigating the relationship between design being researched in laboratory- and practice-based settings, Cash et al. report that, indeed, "laboratory studies are important research tools and that clear and definable relationships do exist between design activity in practice and the laboratory" (p. 575).

3.3 Summary

The design research methods described in this chapter have proven to be valuable when looking at individual aspects of design processes. Traditional methods like protocol analysis or content analysis have produced fundamental insights into how designers work. New methods, like linkography, enhance our understanding of design activities in novel and auspicious ways.

Despite their indisputable contributions, these methods have significant drawbacks. Protocol studies focus heavily on verbal interactions, leaving out many dimensions of social interaction, and seem to be suited only for analysing short instances of designing. Case studies often offer not much more than anecdotal evidence, seem to have the tendency to validate the researchers' hypotheses, and are generally harder to draw generalisations from. When using an observational method – apart from being very time-consuming – the data might be distorted by the observational act itself, i.e. the observer influences the observed situation. When analysing artefacts, one must be aware that they often are mute: thus the inferences drawn by the researcher must be carefully reflected in context, so as not to reach any conclusions that are not supported by the object itself. By offering an abstracted perspective on the design process, linkography detaches the observations from the actual design work and dismisses many dimensions relevant to the design process. Expert interviews are often compromised by the interviewees' subjective thoughts and what seems to be socially desirable in the context of the interview.

There are a lot of methods available to the design researcher. Many have proven to be very valuable and led to important insights into the act of designing. However, they only seem to offer a partial view of the design process. By singling out individual perspectives and thus allowing for a more abstract and clearer view on the data, they provide only a limited picture of what actually happens when people design. What appears to be missing is a way to obtain a more comprehensive and integrated picture of the design process incorporating those methods. The next chapter looks at how a new method enabling such a more holistic picture of the design process has been developed in the course of the research for this thesis.

4

4 Studies of practice and pilot studies

The previous chapters have shown the importance of prototypes and social interactions, proposed in the existing literature, as well as a methodological lack in design research inhibiting a comprehensive picture of the design process. Thus, this thesis set out to develop a new method to enable such an integrated perspective. In this chapter, the way leading up to the definition of the new approach will be described, starting with the studies investigating design practice and moving to testing a more controlled experimental set-up in the pilot studies.

4.1 Studies of practice

The research journey undertaken led from observing design activities in practice to focusing on observable practices in designing. Initially, this thesis set out to observe how designers actually work in their everyday practice. In the early phase of investigating designing in practice, different research methods were used to gain a comprehensive picture of the activities observable in design practice. The main focus of these inquiries has been to gain a better grasp of what aspects of the design process seem to matter most. In their sequential move from exploratory to focused perspectives, the studies conducted have tried to narrow down the multitude of possible design aspects worthy of further investigation.

4.1.1 Exploring expert opinions

In a first attempt to identify relevant classifications and future routes of inquiry, expert interviews were used to explore the views and assumptions of expert designers. Five interviews were conducted with the creative directors of an embroidery company, a graphic design studio, and an industrial design firm, as well as senior consultants of an experience design consultancy and a senior researcher at an academic research group. The interviews were set up as semi-structured interviews. As Robson (2002) suggests, the interviews' questions were predetermined. They concerned the following topics: inspiration, process, trends, culture, prototyping and collaboration. The interviews were audio-recorded and transcribed for further analysis. In a first step, the interviewees' statements have been grouped together in predefined categories and written out for better readability. The interviews were employed as exploratory work, identifying important topics and activities in design practice. The interviews proved to provide a flexible means to discern specific fields of interest. However, expert interviews also have their limitations. As a researcher, it is hard to tell whether interviewees will just say the things they like themselves to hear and that they believe to be important, or whether they actually recount what is the case. This might well distort the view of how things actually are. Researchers then seem to be well-advised to use this method as an approximation and see the results for what they are, verbalised beliefs, opinions and perceptions of the interviewees. As such, these interviews suggested the importance of prototypes, collaboration and inspiration in design practice. The creative director of the embroidery company, for example, pointed to their vast archive of historic designs as a major source of inspiration and design direction. The consultants of the experience design firm highlighted their interdisciplinary team collaboration as a crucial factor to their work. The graphic and industrial designers pointed to their use of prototypes, possessing the critical "power of the real".

However, the interviews were not informative regarding the minutiae of designing. Exactly what kind of prototypes were used and how? When were they used in what way to what purpose? How and where did collaboration take place formally and informally? What kind of collaboration took place when and how? To answer these questions, observing design activities in practice seemed the next logical step to gaining a better understanding of the design process.

4.1.2 Observing designing

"As the actions and behaviour of people are central aspects in virtually any enquiry", Robson (2002) reports that "a natural and obvious technique is to watch what they do, to record this in some way and then to describe, analyse and interpret what we have observed" (p. 309). He differentiates between two classes of observational methods: formal and informal. Informal approaches are characterised by a low degree of structure and allow the observer freedom in what kind of information is obtained and recorded. Formal approaches, on the other hand, specify to a large degree what is being observed. Robson points out that the latter achieve high reliability and validity, but do so at the cost of losing complexity and completeness compared to informal approaches. Therefore, different kinds of observation were conducted at a graphic design studio, an industrial design firm, a research group at Princeton University, an interaction design company, and an experience design consultancy. The results have been published in the proceedings of the IASDR 2011 conference in Delft, Netherlands (Peter, Schadewitz & Lloyd, 2011), and are recounted here in an adapted version.

At the graphic design studio, the dimensions proposed by the contextual inquiry approach according to Beyer and Holtzblatt (1998) were observed and recorded. Beyer and Holtzblatt propose contextual inquiry to "make unarticulated knowledge about work explicit" (p. 37) in order to reveal hidden work structures. The dimensions being observed included: (a) work flow, (b) sequence, (d) artefacts, (c) culture, and (d) physical environment. Of the observations, a spatial layout map and photographic records were made for further analysis (Figure 5 and Figure 6).

The spatial layout map of the graphic design studio (Figure 5) reflected the importance of collaboration and prototypes. The alignment of the computers, allowing easy communication with each other and to see what is on a colleague's screen, as well as the space occupied by the collaborative workplace and the meeting table, indicated a very collaborative work setting. In addition, the collaborative workplace, as well as the cutting and glueing workplace, suggested that prototypes play an important role in the designers' everyday work practice. A third observation revealed how the designers were incorporating inspirational aspects into their work space. A library, with an armchair for reading, provides a source of inspiration. Artefacts could be observed on the walls and shelves that would serve as an inspiration.

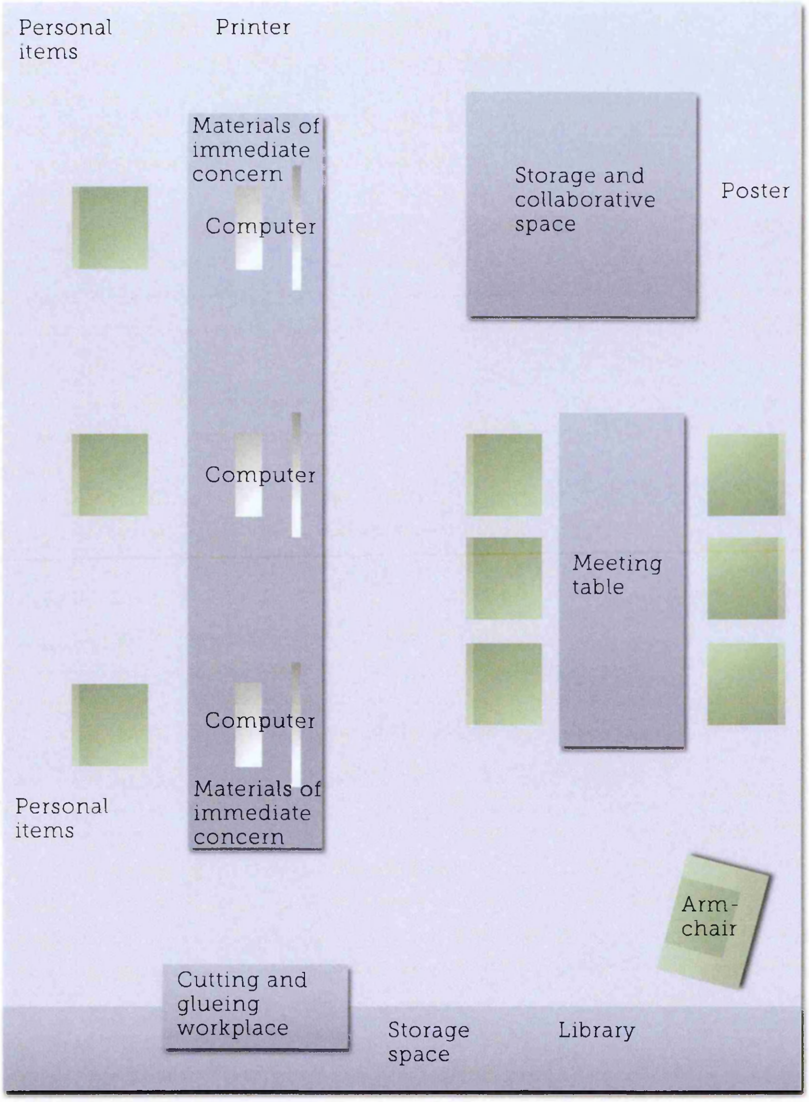
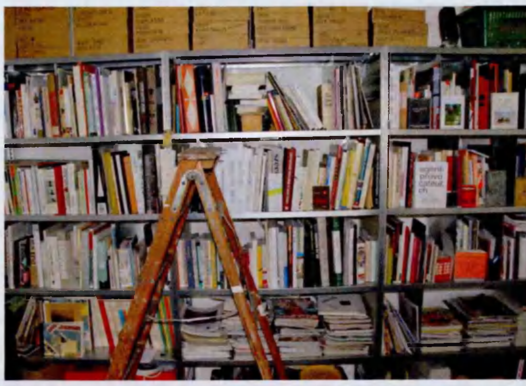
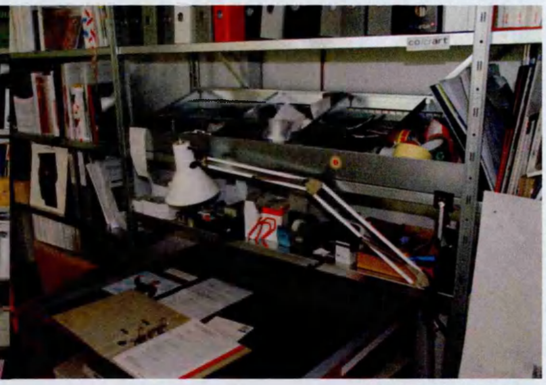


Figure 5: Representation of the studio space at the graphic design studio as part of a contextual inquiry.

The photographic archive corroborated the observations made in the spatial layout map. Figure 6 shows a few pictures taken from the archive, illustrating the observations made, especially regarding the role of prototyping and inspiration in the graphic design studio.





One corner of the bookself is reserved for the book collection.

A small space within the bookself is designated for cutting or glueing prototypes.

A large table serves as a collaborative space and to store paper samples, as well as large-scaled posters.

Visual stimuli are being displayed on the walls.

Figure 6: Sample excerpt of observations made at the graphic design studio as part of a contextual inquiry.

A similar approach was used to observe design practice in an industrial design firm. In several visits, the spatial settings, artefacts, work flows and culture, as well as a design meeting, were photographed and video-recorded (Figure 7 and Figure 8). The observations resulted in a photographic image archive which was analysed later.

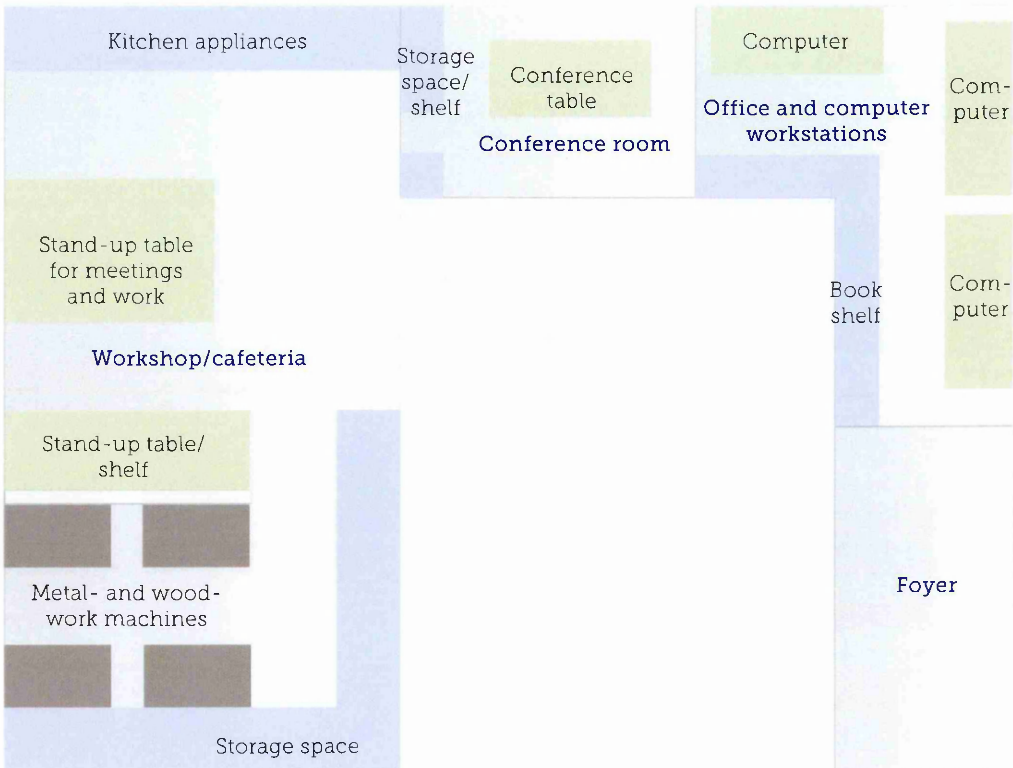


Figure 7: Representation of the studio space at the industrial design agency as part of a contextual inquiry.

The observation regarding the importance of prototyping at the graphic design studio is even more emphasised at the industrial design studio. The combined workshop and cafeteria space occupies half of the entire space. Space for collaborative work – be it informally at the stand-up table in the workshop, or more formally in the conference room – takes up a major part of the square footage.

The photographic archive reflected these observations (Figure 8). Particularly the importance of prototypes to the work in the industrial design studio became apparent, with many prototypes and materials being either displayed in the conference room or stored and awaiting further work in the workshop space.

Figure 8: Sample excerpt of the image archive produced during the visits at the industrial design agency.

In order to structure the observations made in further analyses, a prototyping-centred working model of design activity was devised to categorise the findings along four main topics: culture, communication, conception and coordination (Figure 9). It focused on prototypes, as the observations made up to this point emphasised their crucial role in design practice. It did so by identifying four dimensions: (1) how their role and use are influenced by cultural aspects; (2) how they support communication; (3) how they are conceived; and (4) how their development is coordinated.

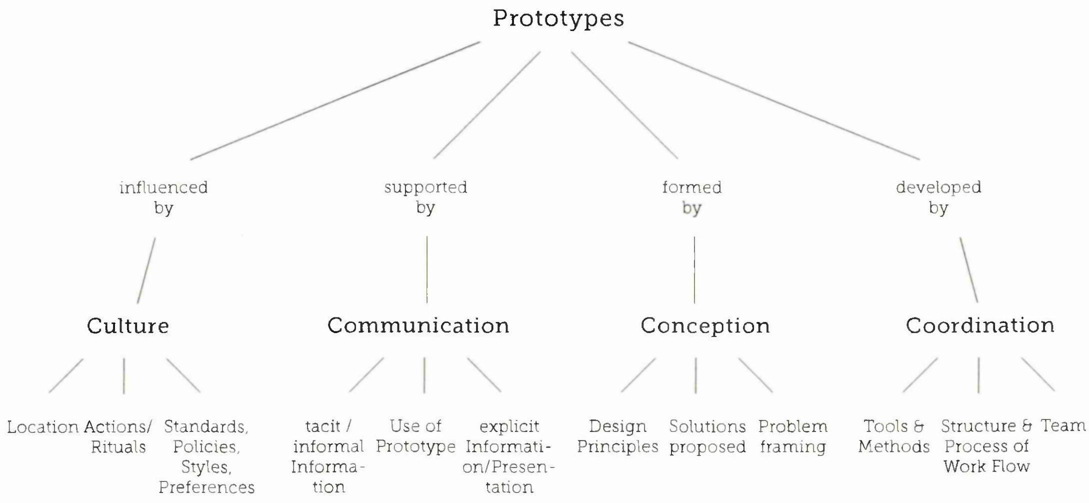


Figure 9: Prototype-centred working model devised to help categorising the observations' findings.

At the experience design consultancy, the process and methods as well as the physical space were recorded in detail. In interviews, first the core routine the company uses when working on an assignment was obtained (Figure 10).

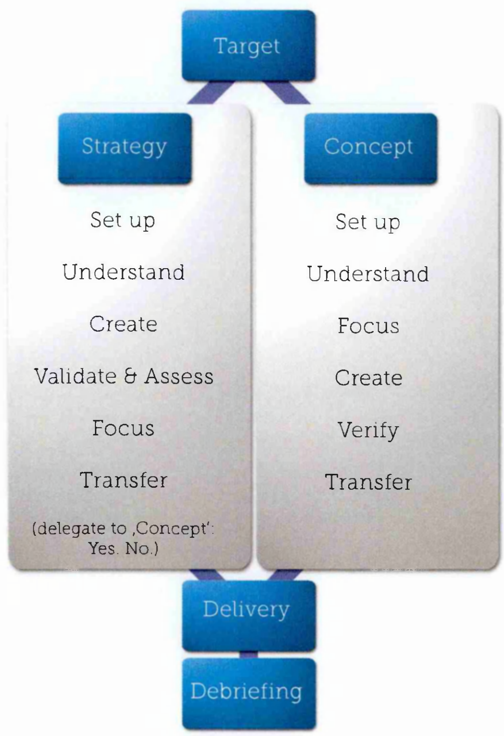


Figure 10: Depiction of the core routine obtained in interviews with senior consultants at the experience design consultancy.

As in the other studies at the design agencies, photographic field notes were taken, with a specific interest in how the designers use physical space and what tools and artefacts could be observed being used (Figure 11). The objective was to gain an overview of the tools and methods with a special focus on the creative process phase. Furthermore, different dimensions derived from the previously defined prototyping-centred model of design-driven innovation were explored.

In contrast to the observations at the graphic and industrial design studio, prototypes in a strict sense were very sparse. The use of Post-it notes as well as flip charts, however, was pervasive. When interviewed, the consultants reflected on their culture as being rather analytical, logic-driven and factual. They see themselves more like smart problem-solvers than creative idea generators. In a way, the term 'experience design agency' might be somewhat less appropriate to describe their work than 'experience analysis agency'.

Figure 11: Unstructured field observations were recorded photographically for later analysis.

A different approach was chosen to analyse design activity at an interaction design company. The company broadcasts a live webcam feed on their website (Figure 12). The design activity displayed in this feed was, in a form of covert observation, video-recorded and analysed in repeated viewings. This was done by looking at the proportion of time spent in activities that could be classified as 'discussion' during the entire two and a half-hour period of the observation, and allowing for the gathering of naturally occurring data in design practice without influencing the observed designers.

This observation revealed the collaborative nature of the work being done at the interaction design studio. Being a company that provides digital design solutions, the prototypes seemed to be limited to the designers' individual computer screens. In a way, prototypes were less pervasive in a spatial sense than observed at the graphic and industrial design studios. However, the webcam feed showed the importance of informal discussions throughout the design process, as the designers spent up to one-third of their time in conversation.

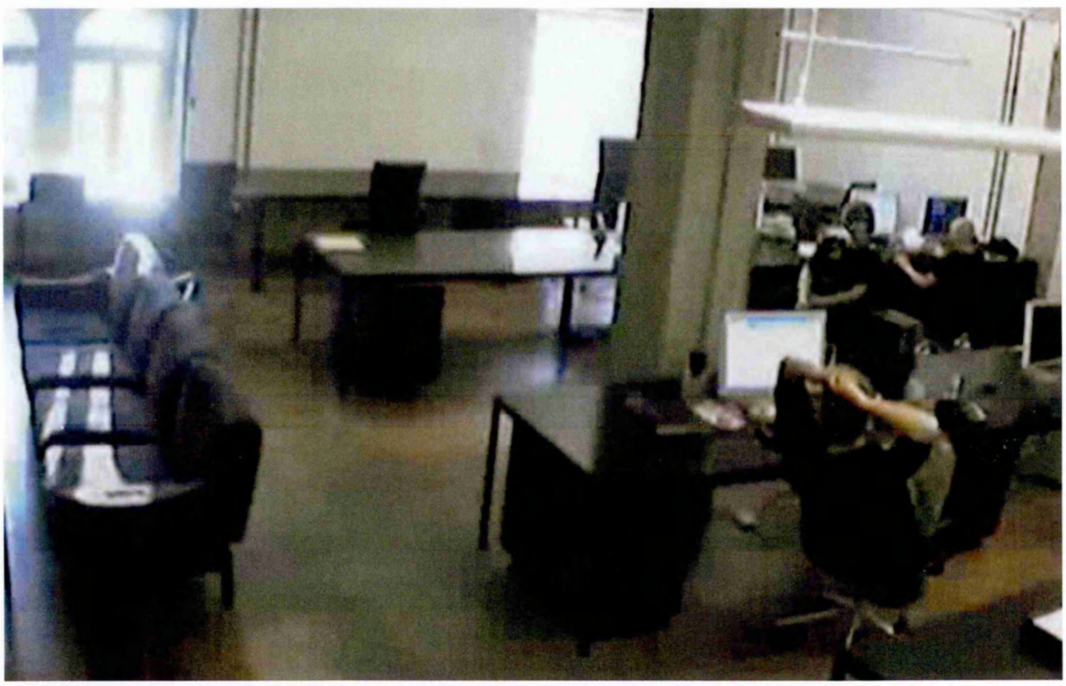


Figure 12: Video feed obtained from a webcam installed at the interaction design studio.

In order to look at creative and innovative processes from a more general perspective, a study outside the design discipline was conducted. At a research group at Princeton University, an observational study could be conducted collecting images of the tools used, artefacts produced, and the physical environment within which the research is located. The aim was to portray a typical research activity being executed by a research group. As in the studies before, a photographic archive was produced for later analysis (Figure 13).

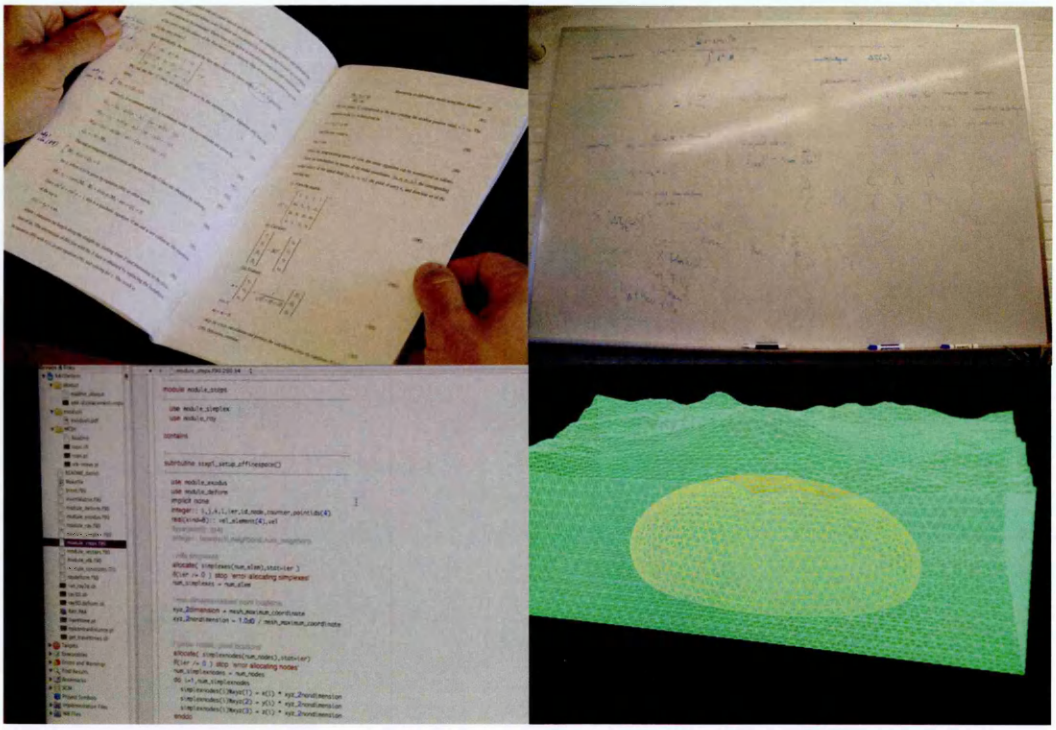


Figure 13: Samples of the visual field notes taken at the research group at Princeton University.

The work done by the researchers could be well described as creative and, to a degree, as visual. However, their primary means of collaboration was found in the form of written articles, mathematical formulas and programming code. Their main aim – in the project observed – was to better understand and measure a geophysical phenomenon, and to apply and test a specific theory to the solution of this problem. Thus, their way of solving problems features some characteristics of the designerly ways of knowing as proposed by Cross (2001), although it seemed more problem-focused and concerned with theory testing than designing an appropriate solution.

4.1.3 Analysing artefacts

Particularly in the studies conducted at the industrial design company and the graphic design studio, artefacts could be photographically documented and analysed. Just as Norum (2008) suggests that "Artefacts can be used to support or challenge other data sources" (p. 24), the data gathered from questioning the artefacts themselves as well as their context was used to cross-reference individual insights with other data sources, i.e. interviews and observations.

Analysing the artefacts proved to be particularly interesting, as 'prototype-rich' environments were found at both the industrial design company and the graphic design studio. Both emphasised that using the 'real' materials provided them with more insight and inspiration than when just designing on the computer screen. The artefacts reflected this approach, and their use in design discussions corroborated their importance in design collaboration. Their different forms and types also indicated that they were used for different purposes during the design process.

However, most of these observations on the artefacts themselves were taken somewhat out of context. In order to analyse them with more knowledge about their usage in the process, in the Princeton study the tools used were noted alongside the individual steps of the process and the form of collaboration taking place (Figure 14). This allowed for a look at the artefacts with more understanding in regard to their place in the design process, or, in this case, the research process.

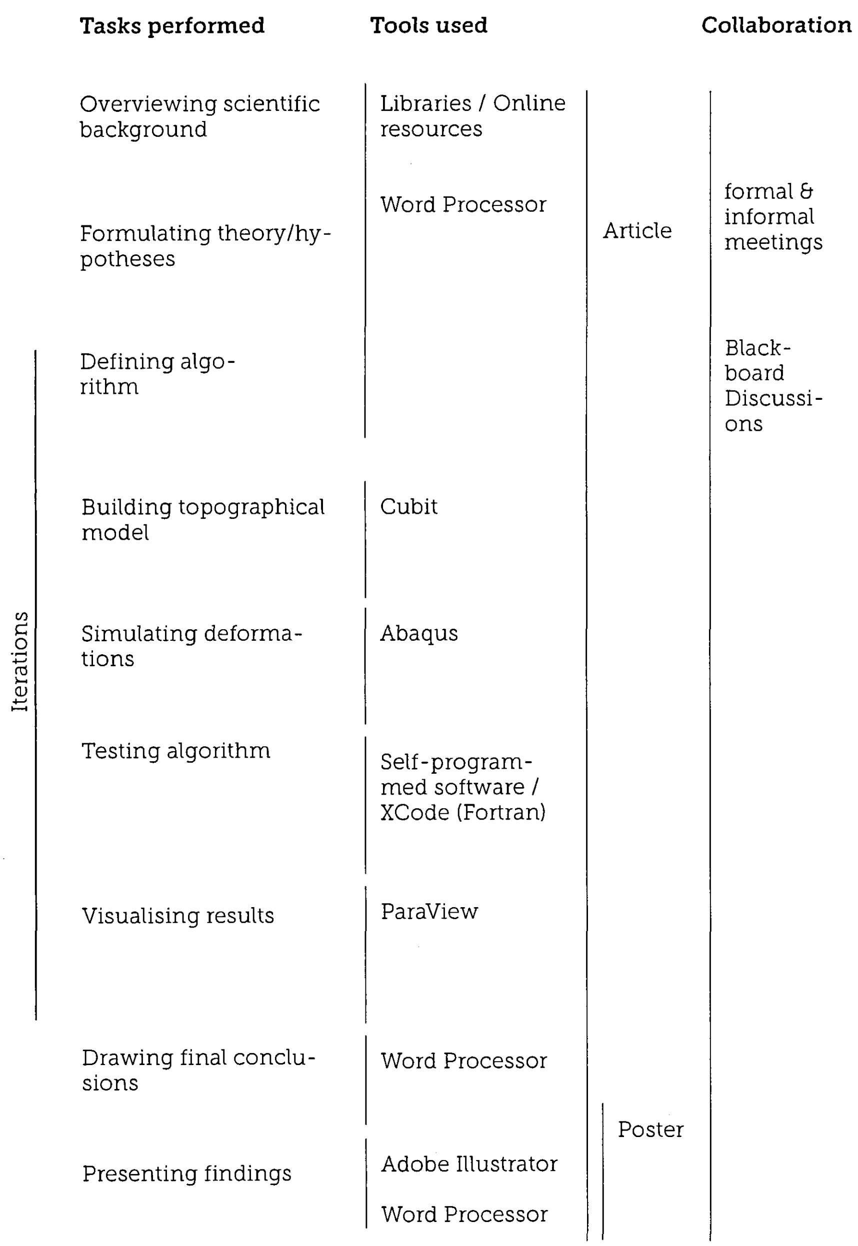


Figure 14: Depiction of the process being employed by the research group alongside the individual tools and forms of collaboration.

4.1.4 Prototyping in the design process

Through close observation of the studio spaces, one of the most distinctive features of design work revealed itself: prototypes can be seen throughout all offices and workshops. In particular at the industrial design company, but also at the graphic design studio, this characteristic is striking. What could be described as a 'prototype-rich' environment dominates the workplace of the designer (Figures 15-17). The need for physical embodiment, which is evident throughout the studio's workshop, is emphasised by the designers, especially when considering the tacit knowledge that prototypes embody.

Figure 15: 'Prototype-rich' environment in an office at a Swiss industrial design firm.

Figure 16: 'Prototype-rich' environment in a workshop at a Swiss industrial design firm.

Figure 17: 'Prototype-rich' environment in a Swiss graphic design studio.

The importance of prototyping in the context of design practice was evident. In design practice, prototypes come in many variations. The shiny object being unveiled by its designer in front of an expectant crowd, that is so often associated with design, is only the culmination of many iterations of prototypes. In design studios, different kinds of prototypes can be seen. Very rough models are used to quickly test and improve functional features. More refined models are being used to assess different aesthetic qualities of an artefact.

The industrial designers observed emphasised moving quickly from drawing design sketches to producing rough prototypes with the specific materials intended to be used in the final design solution. Eventually, they will devise detailed plans and renderings using CAD – mainly for representational purposes or testing specific layouts – but, especially in the early design stages, they rely on rough prototypes (Figure 18). The same approach can be observed in a graphic design studio. While the designers would later on work out their final design of a book using professional layout software, the designers used a paper prototype to develop the design concept (Figure 19).

Figure 18: Rough prototype of a chair used in the early conceptual phase of the design process.

Figure 19: Early conceptual book prototype at a Swiss graphic design studio.

Within the design process at the industrial design studio, the use of different types of prototypes is emphasised in individual development stages but not restricted to them exclusively. Usually, the workflow's process and structure at the studio are defined upfront in every project, with the main phases splitting into: (1) initial research about the problem; (2) briefing with the client; (3) deepening the research; (4) defining the problem; and (5) refining the prototypes. Sketches and prototypes are used from the very beginning of every project. According to the designers, quickly moving from sketching to prototyping would allow them to experiment widely with different materials and to gain initial insights from these experiments. Sketches are used mostly in an early, individual reflection phase and to store first design ideas. Figure 20 depicts an early 'thinking sketch' (Ferguson, 1992), and Figure 21 a 'storing sketch' (Van der Lugt, 2005).

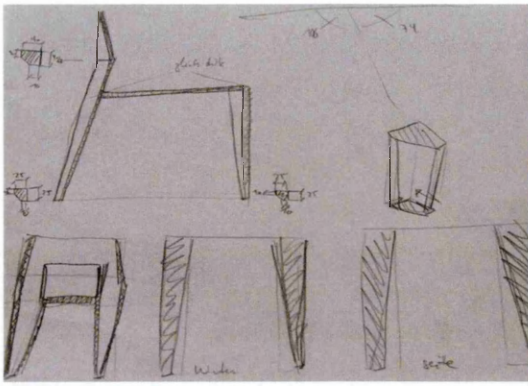


Figure 20: Example of early 'thinking sketches'.

Figure 21: Collection of early 'storing sketches'.

Referring to the ways prototypes are employed, the designers drew a strong distinction between 'function prototypes' (Figure 22) and 'style prototypes' (Figure 23) (Peter, Schadewitz & Lloyd, 2011). The first aims to test a functional feature of a possible design solution, while the latter investigates aesthetic properties.

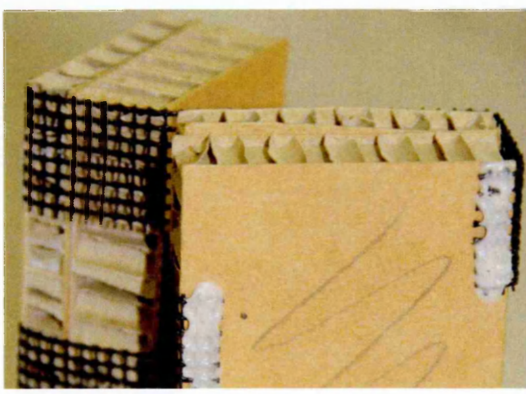
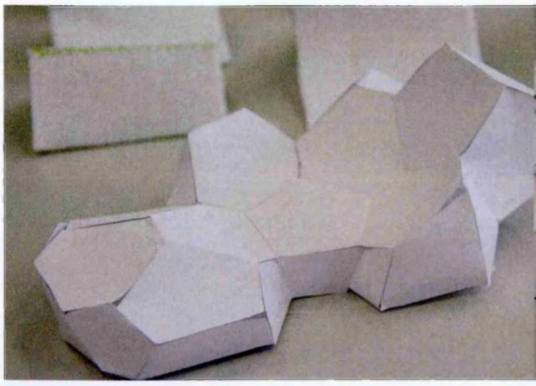


Figure 22: 'Function prototype' used to quickly test a functional feature of a product.

Figure 23: 'Style prototype' used to assess different aesthetic qualities of a product, like proportion.

However, this distinction was difficult to discern in practice. Figures 24 and 25 show prototypes which seem to be abstract studies in style at first glance. Yet, once one realises that these are prototypes for a lounge design, it becomes evident that there are functional elements embodied in them as well: for example, the exploration of structural features of the particular lounge arrangement.



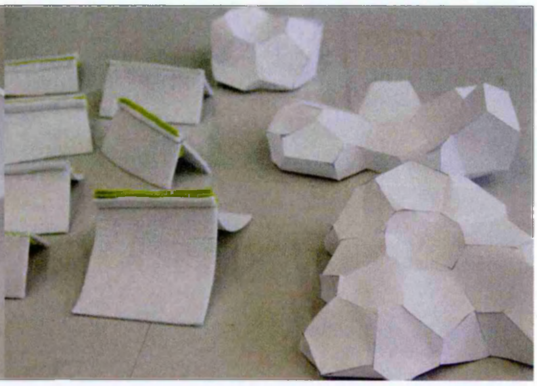


Figure 24: Lounge design prototype.

Figure 25: Samples of different stitching techniques with lounge forms.

A variety of different purposes for which prototypes served could be observed in the design process: prototypes showed specific functionalities, represented shapes or forms, tested stability, proved that they could be mass-produced or served to present a design solution to clients etc. Individual prototypes could converge all of these aspects or focus on a specific purpose. An example for the latter represents Figure 26, a functional prototype testing the stability of a hall stand design.

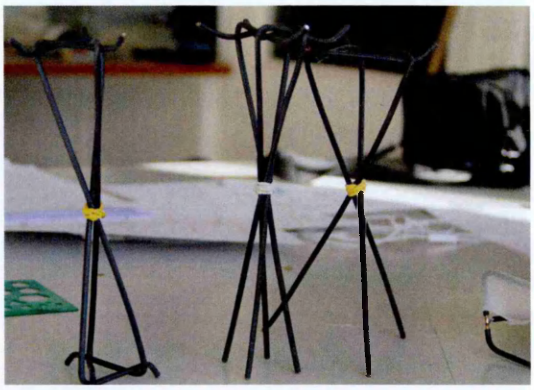


Figure 26: Functional prototype made to test the stability of a hall stand design.

This example illustrates how different types of prototypes are used and evolve in design practice. Once the designer found a solution for the stability problem, a more refined and elaborated model was built. This model incorporated not only the design solution addressing the stability issue, but also other functional problems, such as the joining of the individual elements. However, it represented not only functional solutions, but also stylistic reflections, for example by using the actual material intended to be used in production and by articulating the shapes of the elements (Figure 27).

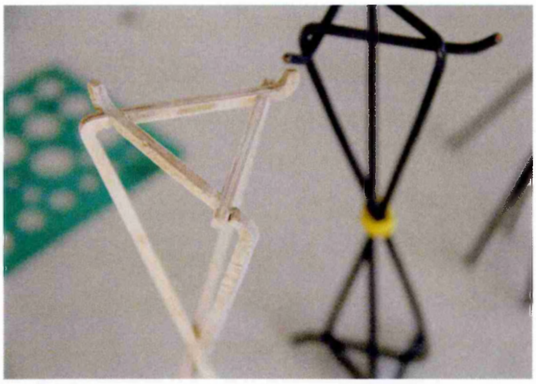


Figure 27: Refined prototype incorporating different functional and stylistic aspects of the design solution.

Stylistic prototypes were widely used in the observed design practice. Figure 28 shows prototypes that reflect on different effects and appearances of materials. These examples are meant to illustrate how the type and colour of a fabric influence the overall appearance of a chair. These prototypes allow the designers to explore the interrelations between functional aspects of the design and the aesthetic effects, and to subtly develop the structural steel frame as different materials were tested.

Figure 28: Style prototypes showing the aesthetic effects of different kinds of fabrics.

Many of the prototypes used could be classified according to the typologies suggested by Budde, Kautz and Kuhlenkamp (1992), Sommerville (1995) and Ullman (2003). Figure 29, for example, depicts an example of Ullman's (2003) category of 'proof-of-production' prototypes. The studio's owner pointed out the importance of such prototypes, explaining that "when the building of the prototype is a tedious and difficult work, chances are that the production of the final product will be too."

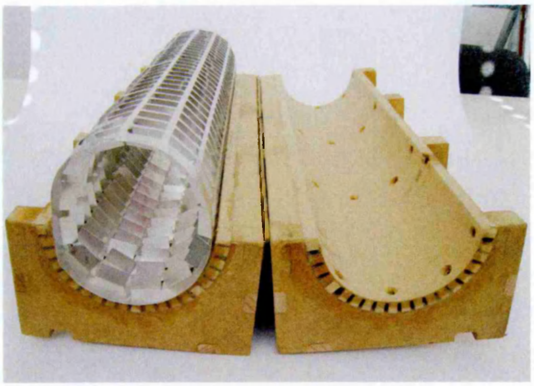


Figure 29: Proof-of-production prototype.

A prototype extrusion for a lamp, as shown in Figure 30, illustrates Yang's (2005) observation of simpler design solutions leading to more successful outcomes. The prototype for a light fitting consists only of two parts and uses gills as cooling elements. This solution allows, on the one hand, for a better heat distribution, and thus a longer lifespan for the LEDs, and, on the other hand, to give the user tactile and implicit information about the ways in which the lamp operates.

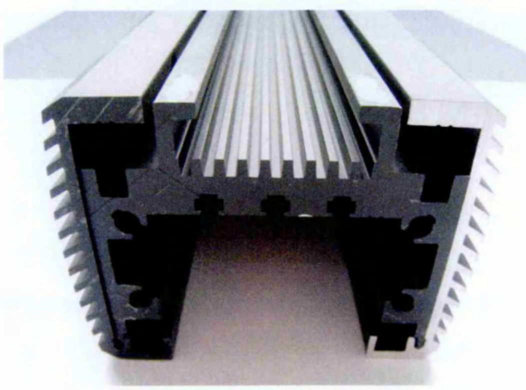


Figure 30: A prototype for a light fitting using only two parts to achieve the desired design solution.

The prototypes described above fit most closely with Ullman's (2003) typology, distinguishing between proof-of-concept, proof-of-product, proof-of-process and proof-of-production. Much thought is given to the kind of prototype and its form when presenting design solutions to clients. Occasionally, rough prototypes are presented deliberately to set the focus of discussion and to leave space for imaginative interpretation. At other times, refined prototypes set within their contexts of use are shown, communicating a final design solution in a more precise manner. This illustrates that prototypes can be employed effectively to set the frame of conversations with clients by judging in advance the kind of discussion the designers want to have in order to solicit the information needed for further design steps.

4.1.5 Discussion in the design process

As prototypes seem to permeate all offices and workshops, it is no surprise that the designers interviewed report that they often ignite informal conversations as well. Pointing to a specific capacity of prototypes, one designer emphasised that they possess the "power of the real" as well as being "playful and sensual", enabling them to facilitate richer discussions than when relying solely on more abstract media like sketching – themes that are echoed by Brown (2009).

While the designers at the industrial design firm use different kinds of media, such as research documentation, project brief, technical documents and brochures, the main focus of their discussion revolves around prototypes. Different kinds of prototypes were used when talking about a specific design concept. The discussion was shaped by the individual artefact's qualities but switched between different aspects of the design solution. The feasibility of specific aesthetic considerations, for example, was discussed using a functional prototype, and vice versa, functional aspects were explored using style prototypes. Additional information was pulled during the conversation from texts and sketches, to investigate different aspects of the topics discussed in more detail (Figures 31 & 32).

Figure 31: Talk occurring during a design discussion led by different types of prototypes.

Figure 32: Discussion of aesthetic properties of a design solution on a functional prototype.

The importance of design discussions could also be observed in the interaction design firm. Investigating the role of design discussion in the design process in more depth, a webcam video obtained from a website feed of the interaction design studio was used (Figure 33). The video, lacking any audio recording, was analysed focusing on the design activity that could be observed. This was done by looking at the proportion of time spent in an activity that could be obviously classified as 'discussion'. A period of two and a half hours was observed.

Figure 33: Observational study using a live-streaming webcam.

While the work environment could much less be described as a 'prototype-rich' environment, in the sense that few models and objects were inhabiting the work place, conversations took place frequently and in different forms (Figures 34 & 35).

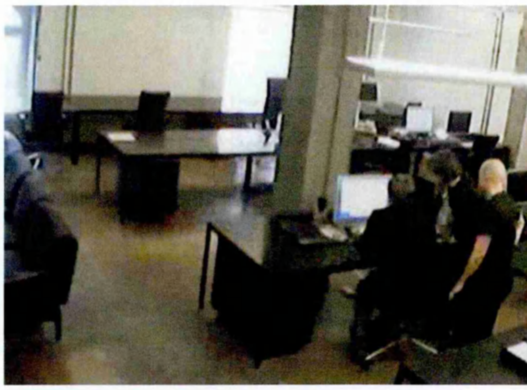


Figure 34: Discussion between designers in front of a computer screen.

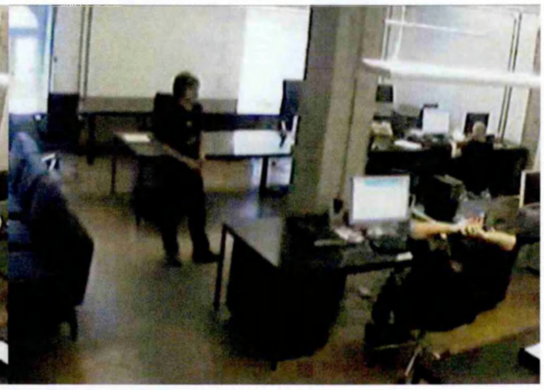


Figure 35: Casual talk held between the desks.

The analysis of the video feed of the webcam installed at the interaction design firm showed that designers spent almost 40 percent of their time discussing their work (Table 1). While different kinds of discussion could be identified, like conversations led without leaving one's desk – indicating a less formal discussion – or participants gathered around a computer screen, the comparison of the time spent discussing and working silently was revealed, too. The designers' decision to invest more than one-third of their observed working time in conversation points to the conclusion that discussion is an important and integral part of everyday design activity.

Type of Discussion	Duration	Proportion of Time
Between two people in front of computer screen	27 Min 15 sec	18.3%
Between three people in front of computer screen	2 Min 32 sec	1.7%
Between two people from their desks	19 Min 30 sec	13.1%
Between three people from their desks	6 Min 40 sec	4.5%
Between two people at one desk	3 Min 28 sec	2.3%
No discussion	1 Hour 29 Min	60.1%
Total Observation Time	**2 Hours 28 Min**	**100%**

Table 1: Different forms of discussion observed (Peter, Schadewitz & Lloyd, 2011).

Discussions and roles

One way to interpret the results obtained is to see the form and frequency of discussions indicating different roles performed by the designers observed in the studio. The designer at the desk in front of the frame appears to hold some sort of supervising function. The two co-workers addressing him regularly, while they do not seem to discuss anything amongst themselves, seem to suggest such an interpretation. The designers were regularly addressing the 'supervisor', who then went to their desks, seemingly to give feedback or guidance regarding their work. On the few occasions when the designers joined the 'supervisor' at this desk, the gestures seemed to denote some sort of reference, or that an example was shown to them. In another observation, the 'supervisor' hardly uses his keyboard, while the two designers at the back of the office were using theirs quite often, further reinforcing the suggested roles.

The meetings take place at individual workstations, or as occasional conversation from the co-workers' desks, indicating an informal nature of discussion. Since the video recording did not allow us to discern what their screens were displaying, it is difficult to know what the discussions were actually based on. However, it seems safe to say, due to the services offered by the firm, that they involved some sort of web-based interface design. The assumption is made that any activity taking part in a professional design practice constitutes part of a design process since work, in a general and self-evident sense, is being done.

However, while it may not be obvious what exactly was discussed and developed during the period observed, Table 1 shows that more than one-third of the time was spent discussing the work. About the same amount of time was spent casually discussing from the desks and more formally discussing in front of an individual designer's computer screen. In some respects, the high frequency of discussion was surprising. Particularly, as the discussions occurred as many spontaneous and brief conversations, instead of single, long meetings. It could not be discerned, whether this was related to the specific kind of work accomplished during the observational period, the prevailing corporate culture at the design firm, or some other reason.

Types of discussion and spaces

The types of discussion observed at the interaction design agency were compared with those at the industrial design studio. Certain similarities could be found: casual conversations, carried out in a very informal manner, with a cup of coffee in the kitchen or at the desks, seem to take place frequently. At the industrial design studio, most group discussions took place in the kitchen/workshop area (Figure 36). In the main conference room, more formal discussions were held, for example, with clients (Figure 37). This room has a more serene atmosphere, but still plenty of prototypes permeate the space.

Figure 36: Stand-up table for informal meetings, and expample of a 'prototype-rich' environment.

Figure 37: Conference room for formal meetings.

While the conference room allowed for a focused discussion of individual prototypes, the stand-up table in Figure 36, being a part of the workshop, opened up conversations in a more playful manner. Current work and different materials infusing inspiration in the design process were lying around the workspace, provoking easy ways to switch topics of discussion. A striking difference between the two studios is the difference in the number of prototypes. In the industrial design studio, prototypes of design activity were strewn everywhere and seemed a constant source of discussion. At the interaction design firm, the picture was completely different. While at Studio Beat Karrer the space could be described as a 'prototype-rich' environment (Figure 38), at R.O.S.A. the office space appears to be clean and relatively 'prototype-poor' (Figure 39). Although, prototypes might be numerous in digital form at R.O.S.A., they would seem to be very much confined to the computer screens and do not at all permeate the studio's space itself.

Figure 38: A 'prototype-rich' environment at the industrial design studio.

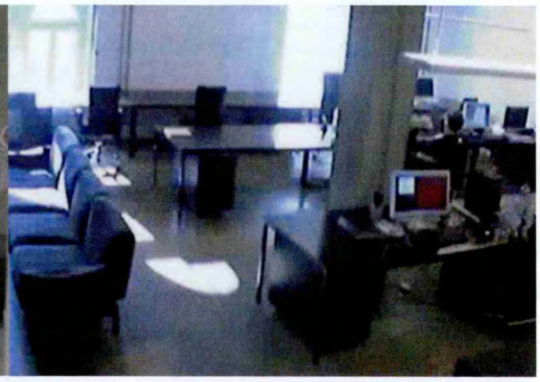


Figure 39: A 'prototype-poor' environment at the interaction design studio.

Focusing prototypes

Another observation made in these studies concerned the 'focusing' nature of prototype discussions. Figure 40 and 41 depict two designers at the industrial design studio discussing functional properties and aesthetic consequences in different kinds of prototypes. The focus of the two people in discussion clearly converges on the prototype.

Figure 40: Designers' attention converging on a style prototype.

Figure 41: Designers discussing a function prototype.

While exchanging and conveying their ideas and insights with each other, trying to gain common ground, the designers used a variety of different artefacts, such as 'talking' sketches (Figure 42), as well as functional and style prototypes.

Figure 42: Designers using 'talking sketches' during the conversation to gain common ground.

4.1.6 Conclusions

These early empirical studies yielded valuable insight into the importance of individual design activities in practice. The methods used indicated possible fields of interest that promised to be of value for further research. Prototyping and design discussions could be especially identified to play major roles in the production of design outcomes. While interviews were instrumental to understand the designers' opinions and perceptions of their design process and its aspects, direct observation and artefact analysis offered a way to cross-reference the data and individual insights.

However, the methods used produced only certain kinds of data and did not allow for any further deepening of the investigation into the relationship between prototyping and design discussions. How exactly is prototyping being used during the design process? How do designers interact with prototypes during design discussions? Do they have some influence over what and how the designers converse? Do the materials chosen for prototyping have any significance, and if so, which? These questions could not be retrieved with validity using the traditional methods. Expert interviews are prone to give biased information. Observing design activities in practice is often severely limited by issues like access, project duration and confidentiality. In addition, the very practical requirements to gathering appropriate data that is meaningful in a scientific way – for example by controlling different variables of the design process – seems contrary to how design solutions are being achieved in practice.

Questions like the ones above were motivated by the findings made in the unstructured field observations. However, answering them requires a different, more structured investigation into the effects of prototyping on verbal and non-verbal interaction. A new method was needed at this point to answer the questions posed by the preceding research. In a series of pilot studies, this thesis aimed to develop such a new method.

4.2 Pilot studies

In order to address the limitations of the research methods used in the early phase of this thesis, particularly in regard to their open-endedness, a new approach was needed better suited to the specific research interests evolving from earlier findings. The requirements posed to such a method were to enable the observation, recording and analysis of the roles prototypes play in design discussions and the relations between them. Conducting such investigations in design practice is hard to negotiate. Matters of confidentiality play an important role when designing for clients. Early on in the course of this research, it became evident that such issues will, more likely than not, impede any attempt to conduct a series of such investigations in design practice. Furthermore, experiences made suggested that observing design discussions in various practices would prove to be difficult to compare due to the contextually influenced nature of such conversations. Thus, the decision was made to use a research method that would allow for a more controlled and comparable investigation: the controlled experiment.

4.2.1 Testing the set-up

Prior to conducting the main study, a pilot study was devised to test different experimental set-ups (Figures 43). In addition, the pilot study aimed at gaining a better understanding of what kinds of data could be obtained and what analyses produced insightful results based upon these designs. The experiment's original research design intended to observe and analyse randomly chosen groups of designers collaborating on a predetermined design brief using three-dimensional prototyping media, and sketching for the control groups, respectively. In the course of the pilot study using eight experiments conducted in iterative steps, different variables were explored, such as the group size, the individual prototyping materials provided, different design briefs, but also more technical issues such as different ways of audio and visual recording.

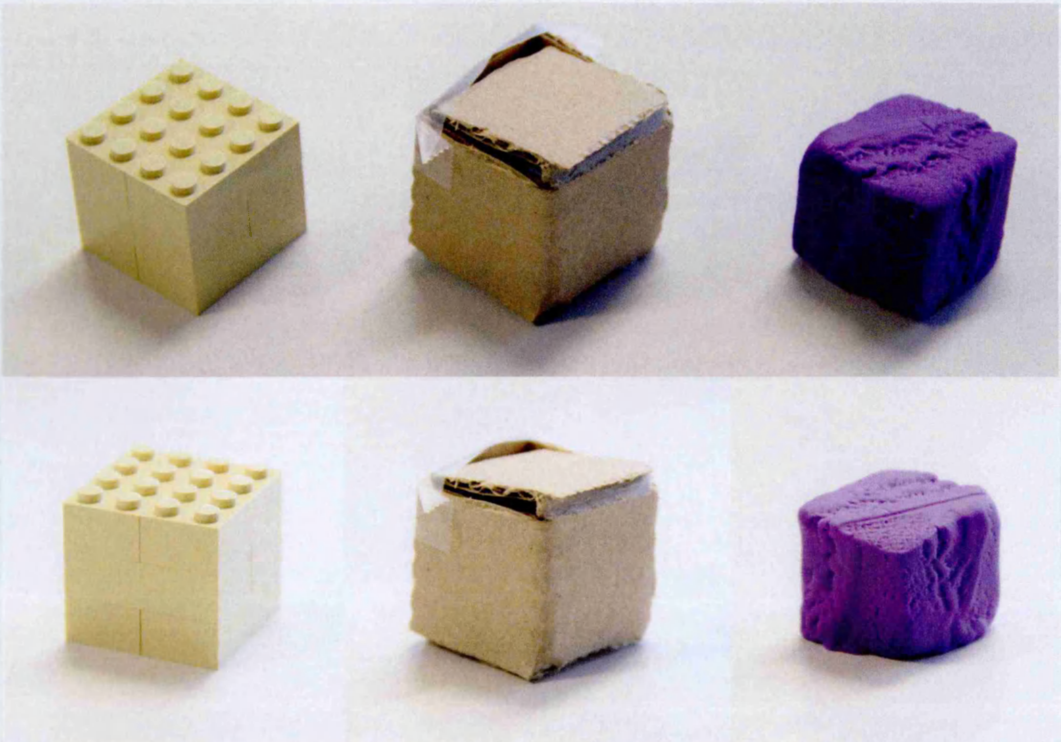
Figure 43: Test of different settings and materials for the experimental setup in the pilot study.

The experiment was set up in two individual tasks. In the first task, the participants were asked to build a square cube with each of the materials provided (Figure 44). In the second task, the participants were given the actual main design task, which was to build a prototype of an electronic device that would enable the users to convey gestures of loving and care to their loved ones. The skill-building task was given, on the one hand, to familiarise the participants with the materials. On the other hand, this task allowed for a focus on the prototyping process with each material in a very controlled manner. Initially, the skill building task was given to build the highest tower possible with each material. This task, although it seemed to motivate the participants to engage more in this activity, proved to somewhat exhaust their creative potential. After finishing this task, the eagerness to produce something else creatively decreased. It also represented a rather well-defined design challenge, to build a high tower, which did not reflect the proposed, more indeterminate nature of design problems. Thus, the task to build a square cube was given. This, in a way, more open task allowed the participants either to build a very simple solution, or to freely interpret the challenge. In the tests, this proved to somehow increase the eagerness to build a creative solution in the main design task.

In testing the set-up, the materials were presented to the participants in uniform boxes. They were all presented at the same time. In the sketching condition, only a pen and paper were provided. This was done in order to be able to infer any preferences regarding the materials used, by recording which material was chosen first, which second, and which third for the skill-building task.

For the main design task, the participants were free to choose whichever material or combination of materials to use, except those in the sketching condition. In the final set-up, the experiments were grouped into three categories: (1) experiments where all three prototyping materials would be provided; (2) experiments where only sketching materials would be provided; and (3) experiments where all three prototyping materials, as well as sketching materials, would be provided. This allowed for an investigation into the interplay between individual materials. In the pilot studies, for example, Lego was mostly used to prototype or represent functional aspects of a design solution, while clay was used to illustrate aesthetic properties. In addition, the use and purpose of sketching in the design process could be better observed in this set-up.

Skill Building Task: Cubes



Design Task: Communication Device

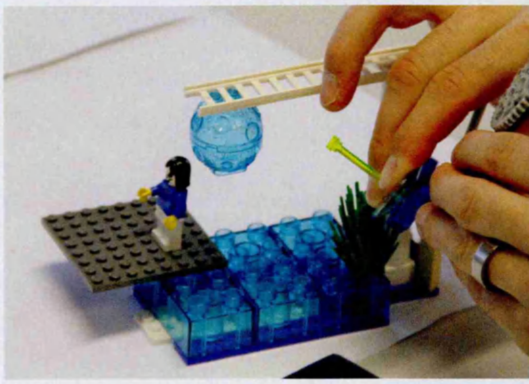
Figure 44: Sample excerpt of artefact documentation of each experiment in the pilot study.

4.2.2 A first analysis

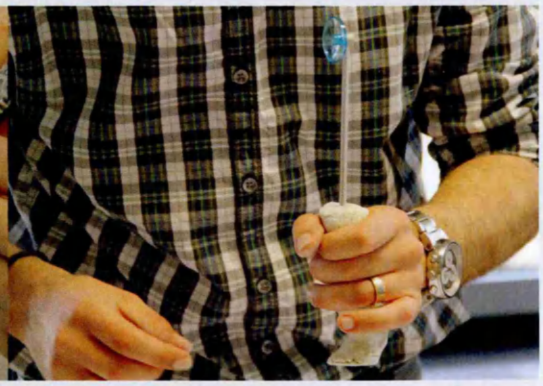
Since it was not clear what kind of data exactly the experiments would yield and what analyses they would enable, the first step was to describe what could be observed in the pilot studies. To do so, the focus was laid on behaviour, artefacts and communication (Figure 45). These first attempts at extracting insights from the data led to more specific questions regarding the quality of discussion and possible indicators for individual types of those qualities.

Teamwork did not emerge naturally from the beginning. One team member started building while the others were still discussing.

The group split the task, some building a 'receiver station', others a 'mobile controlling device'.



The 'receiver station' with a figure, impersonating a significant other, which is controlled by the person that it represents.



The remote controlling device, with which someone transmits gestures, which are then performed by the figure at the 'receiver station'.

Figure 45: Sample excerpt of observations made during the experiments in the pilot study.

In a first attempt to make sense of the data, the number of words, the times the material boxes were used, and the number external references brought into the discussion were recorded (Table 2). Four experiments from the pilot series were chosen for these analyses. In a first step, the audio feeds of the experiments were transcribed. Subtracting all annotations, such as gestures performed at particular moments during the experiments, the number of words used in discussion was derived from the transcripts. In the next step, the number of instances the participants reached into one of the material boxes was recorded. This was done by carefully analysing the video footage of the experiments. In the final step, the number of external references was counted. This was done by combing through the transcripts for instances where the participants brought concepts into the discussion that referred to already existing artefacts or entities.

	Experiment A	Experiment B	Experiment C	Experiment D
Number of words used	1'151	1'245	618	467
Number of times boxes were used	Clay: 3 + 0 = 3 Card.: 6 + 4 = 10 Lego: 37 + 46 = 83 Total: 96	Clay: 1 + 1 = 2 Card: 3 + 4 = 7 Lego: 9 + 26 = 35 Total: 44	Clay: 4 + 1 = 5 Card.: 5 + 5 =10 Sketch: 1 + 0 = 1 Total: 16	Clay: 3 + 3 = 6 Card: 6 + 7 = 13 Sketch: 1 + 0 = 1 Total: 20
Number of external references used	2 / Postmodernism / Dice	4 / IKEA box / Water cube / Wings / Sun-blinds	0	1 / Christmas gift

Table 2: A first attempt of making sense of the data retrieved.

In a second test of different analyses, the number of questions occurring (intended to measure the level of exploration in talk), the number of spontaneous expressions (level of immediateness of talk), the number of evaluative expressions (level of evaluation or performance orientation), and the number of words used by each participant (level of dominance) were being counted (Table 3). This first test indicated that in analysing the talk occurring in the experiments, the analysis had to incorporate a very specific coding scheme containing the exact words that it is looking for and the categories they belong to. After completion of the test, some of the analyses promised to yield results that would illuminate the relationship between prototyping and the conversation occurring with them. For example, when using Lego a significantly higher amount of words could be counted, compared to sketching. Less accentuated but noticeable, this was also the case for the other three-dimensional prototyping media. However, this analysis did not allow for any deeper investigation into why this difference was occurring and to evaluate the significance of the observation.

Test Analysis				
	Sketching Video A	**Cardboard Video C**	**Clay Video A**	**Lego Video C**
Number of questions (0:00 - 4:00 min)	10	8	8	12
Comments: Within this analysis different types of questions could be discerned, which further analysis would have to carefully distinguish: (1) questions related to understanding, (2) suggestions posed as questions, (3) action-oriented questions, (4) evaluative questions, (5) questions posed by bodily expressions.				
	Sketching Video A	**Cardboard Video C**	**Clay Video A**	**Lego Video C**
Number of spontaneous expressions (0:00 - 4:00 min)	5	4	9	10
Comments: The spontaneous expressions have been rather difficult to classify if they are not defined in a very narrow and specific sense. Possible categories could be: (1) expressions of surprise (like: oh! ah!), (2) expressions of an on-going, individual reflection (like: ehm, uhm, sentences fading out)				
	Sketching Video A	**Cardboard Video C**	**Clay Video A**	**Lego Video C**
Number of evaluative expressions (0:00 - 4:00 min)	14	8	9	10
Comments: This analysis posed the same problem of how focused the definition of evaluative expressions should be. Words identified include: good, bad, I like, I don't like, fine, cool, perfect, shit, right, wrong, doesn't matter, working, not working, longer, shorter, sort of, best, worst				
	Sketching Video A	**Cardboard Video C**	**Clay Video A**	**Lego Video C**
Number of words (0:00 - 4:00 min)	P1: 79 (50%) P2: 79 (50%) Total: 158	P1: 136 (48%) P2: 147 (52%) Total: 283	P1: 83 (42%) P2: 115 (58%) Total: 198	P1: 246 (68%) P2: 117 (32%) Total: 363
Comments: This analysis is one of the two proposed analyses to identify whether one participants has a greater expertise in a specific material than the other. It showed that in some circumstances it might be a good indicator (like in the example of Lego Video C where participant A1 is an architect), but needs to be supported by at least one other analysis (like the proposed count of accepted design solutions). However, still many variables play into the perception of the expertise in these experiments like personal traits or the nature of the experimental setup itself.				

Table 3: Test analysis of four different video segments using sketching, cardboard, clay and Lego as prototyping media.

4.2.3 Towards a more visual analysis

After finding it difficult to discern possible correlations, three experiments were analysed using a more visual approach. To that end, different characteristics of talk were plotted in steps of five seconds along a timeline (Figures 47 & 48). The characteristics measured were: the number of words used, the number of spontaneous expressions, the number of evaluative expressions, the number of expressions indicating shared ownership, the number of disagreements, the number of tentative expressions, and the length the two participants shared one of the colour-marked spaces. All three videos used were recorded with the same participants using different prototyping materials. To plot the length and location of interactions in a standardised way, a colour-coded grid was laid over the video feed (Figure 46). The red area marked the space that lay between the two participants and represented the 'hot zone' for design interactions. The yellow area indicated an extended interpersonal space. Blue indicated the space which could be characterised as least interpersonal in nature. In order to reduce the distractions from the movement in individual zones, a soft focus effect was applied. For every 5-second step, the number of participants being active in one of the three areas was recorded.

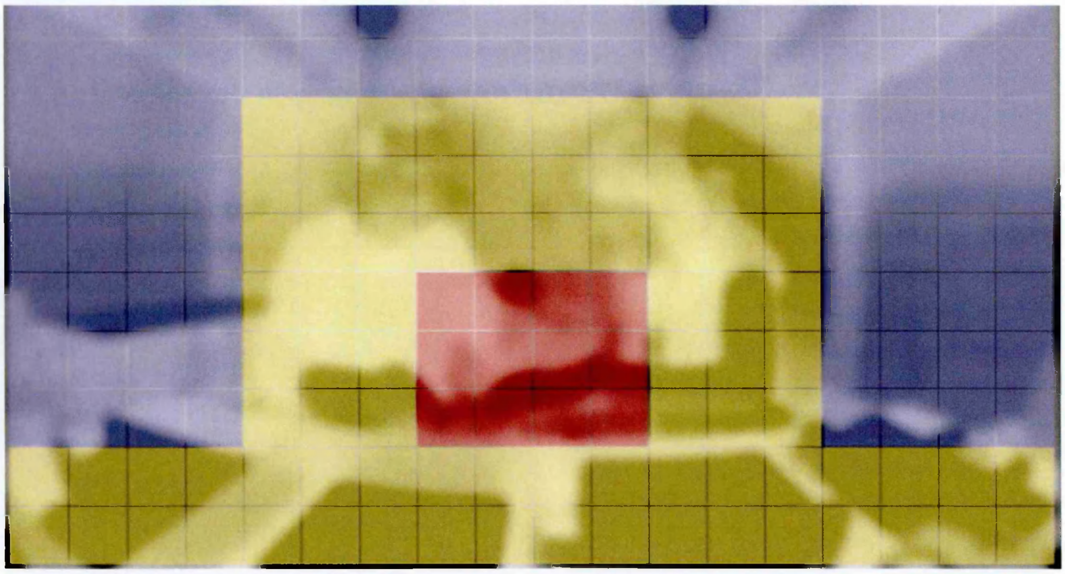


Figure 46: Video recording combined with spatial grid to identify the use of different zones of the interpersonal space.

Figure 47: Analysis of experiment using sketching as prototyping medium.

Figure 48: Analysis of experiment using clay as prototyping medium.

The visualisation proved to be a valuable method to represent and analyse the data gathered. By looking closely at the recordings, the data revealed otherwise hidden information. For example, using Lego as a prototyping medium the analysis showed that while the two participants were both active in the middle of the interpersonal space, the number of words expressed was attenuated (Figure 49). This indicated that possibly another form of thinking was employed, not easily verbalised.

Figure 49: Analysis of experiment using Lego as prototyping medium.

They also showed that in the sketching experiment, the expressions indicating a sense of shared ownership of the design solution (e.g. ours, we, etc.) were most numerous at the beginning of the task and levelled out during the experiment (Figure 50). This was quite in contrast to the experiment using Lego as a prototyping medium, where these expressions occurred continually over the duration of the experiment.

Comparison of the number of expressions of shared ownership

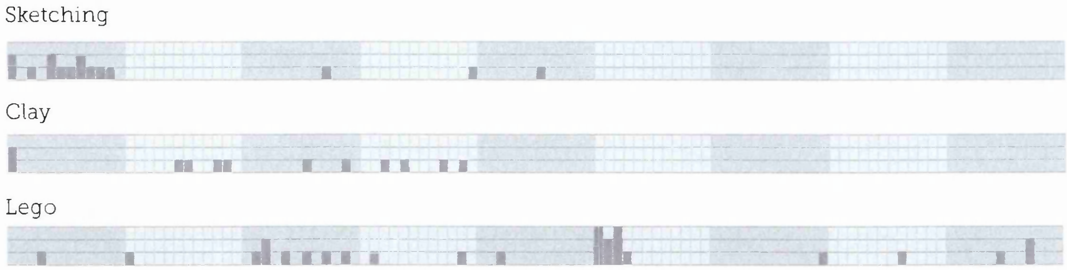


Figure 50: Comparison of the use of expressions of shared ownership using three different prototyping media.

Spontaneous expressions like 'ah!', 'oh!' and 'uhm' were grouped rather closely in the sketching experiment, while being more dispersed in the Lego and clay experiments, indicating that a less spontaneous conversation is taking place when drawing (Figure 51).

Comparison of the number of spontaneous expressions

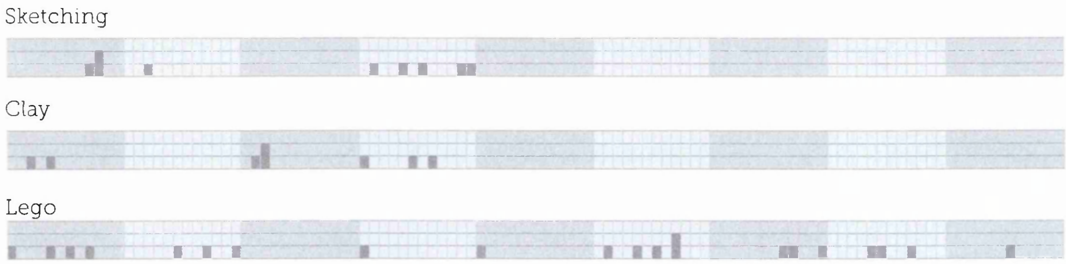


Figure 51: Comparison of the use of sponatenous expressions using three different prototyping media.

The most evaluative expressions like 'good', 'cool', 'nice' or 'bad' were recorded in the clay experiment while the fewest occurred in the sketching experiment. This might be due to the lack of interaction and shared ownership in the sketching task (Figure 52).

Comparison of the number of evaluative expressions

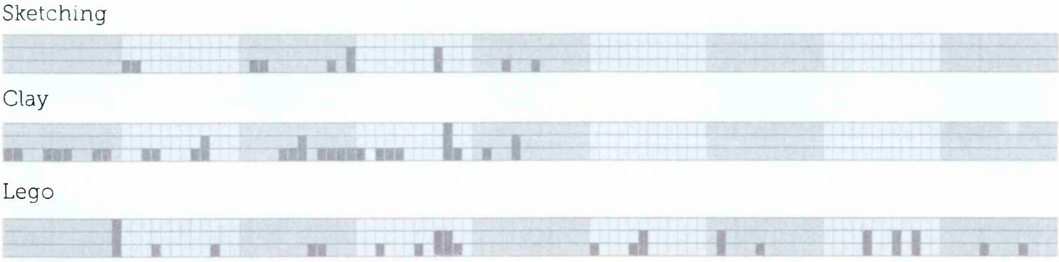


Figure 52: Comparison of the use of sponatenous expressions using three different prototyping media.

In the sketching and clay experiment, most tentative expressions like 'what if?', 'let's say' and 'why don't we?' were recorded within the first two minutes, while in the Lego experiment those expressions were more equally dispersed over the whole duration. Furthermore, the few tentative expressions in the Lego task might lend themselves to the interpretation that talk occurring within those tasks could be more direct and object-based in nature (Figure 53).

Comparison of tentative expressions

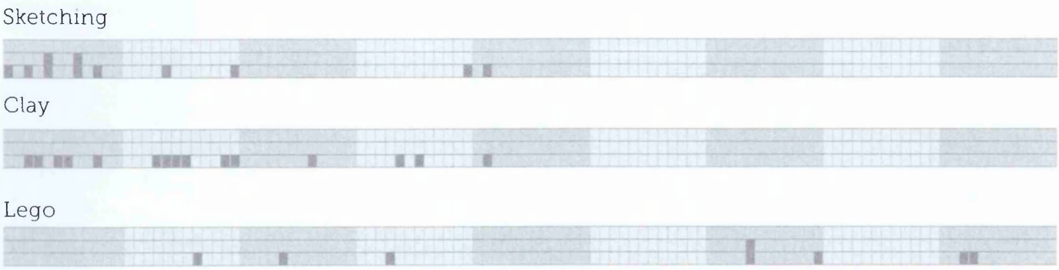


Figure 53: Comparison of the use of tentative expressions using three different prototyping media.

These analyses did provide relevant insights into the design process. What was left unanswered, however, were questions of how the designers working together in these experiments actually used the space between them. This became a more dominant issue as the analyses showed very significant differences in the use of the shared space, especially in the red zone, where intense collaboration on the design solution was assumed to happen (Figure 54). Using the video grid, the majority of time for each 5-second period, where each participant was active in one of the interpersonal spatial zones was plotted on a timeline. In the sketching experiment, for example, the two participants only interacted in this zone in three short instances. While one of them was using the space extensively, the other participant was not in this zone. When using clay or Lego, on the other hand, both participants were involved in the interaction in the red zone in more or less equal shares. However, the analyses did not reveal the kinds of activity actually taking place in those instances.

Comparison of occupation of interpersonal space

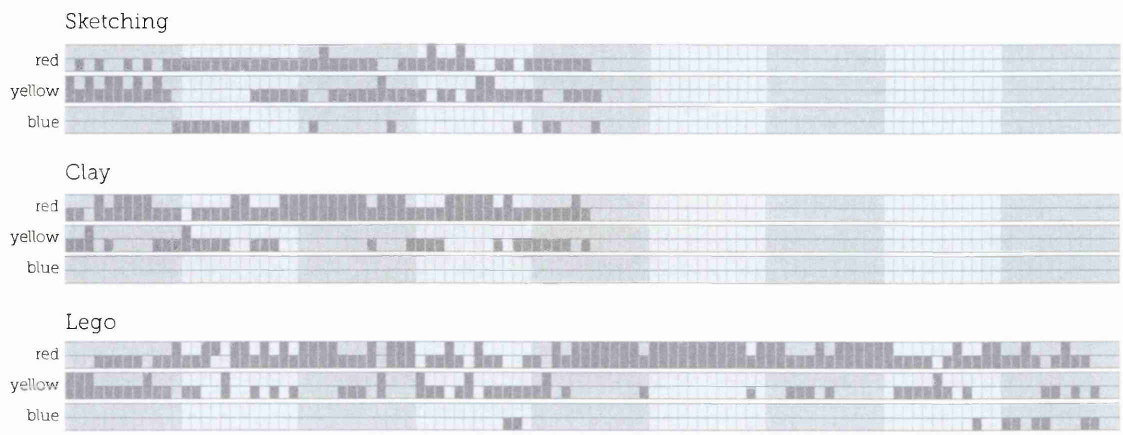


Figure 54: Comparison of the use of interpersonal space between the participants using three different prototyping media.

While there are different kinds of categorisations of gestures, according to Cutica and Bucciarelli (2011) most gesture types, identified in current typologies, can be attributed to one of three main categories: deictic gestures, which comprise indicative or pointing acts; representational gestures, which represent actions, characteristics, forms or relationships between people and objects; and motor gestures, which are rhythmic or repetitive hand movements that do not refer to the semantic content of the accompanying talk. These three distinct kinds of gestures were again plotted along the timeline, allowing for a comparison of what types of gestures occur at different stages of the prototyping process (Figure 55).

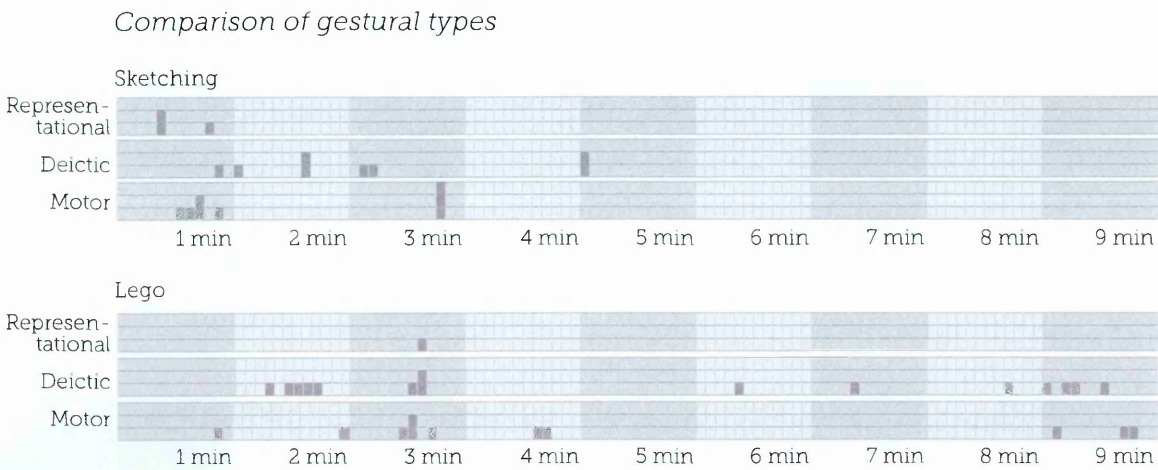


Figure 55: Comparison of the use of different types of gestures using sketching and Lego as prototyping media.

4.3 Summary

This chapter showed how this thesis's inquiry into the collaborative design processes led from unstructured observation in design practice to a controlled investigation of co-located design collaboration, and eventually to a more visualised way of data analysis. In the studies of practice, expert interviews allowed us to gain a general understanding of the interviewed designers' perception of their design processes. However, these insights had to be interpreted with prudence, as they can be easily distorted by the interviewee's own beliefs and social desirability bias. Directly observing design practice offered a more objective way of analysing design activities.

The observations made in these practice studies allowed to identify many types of prototypes suggested in previous work, particularly the typologies of Budde et al. (1992), Sommerville (1995) and Ullman (2003). They also support Oak's (2010) claim that communication and negotiation are central to design, confirming her observation that design practice is deeply discursive and contextually specific. The designers spending one-third of their time discussing indicates the importance of conversations in the design process.

Different kinds of discussion could be observed in design practice, ranging from formal to casual conversations. A distinction between 'prototype-rich' and 'prototype-poor' environments could also be made. The 'focusing' nature of discussions around prototypes not only suggests that such spatial environments may influence the kinds of conversations taking place, but also that, as the designers at the industrial design studio mentioned, prototypes enable discussions about embodied design issues, sometimes referred to as tacit knowledge, which is an often overlooked feature of the design process in professional practice.

In a more general sense, the data gathered and results obtained reveal two key aspects of the design process: prototyping and discussion. They also raise the question as to how exactly prototyping and discussion are related to each other. More specifically, while the unstructured field observations reveal the importance of prototypes in design discussions, they cannot disclose just what effects different types of prototypes and prototyping materials have on the discussions taking place around them. What kind of discussions, for example, does the use of three-dimensional prototypes enable and how does it differ when discussing sketches? Are there differences in design discussions when using unstructured materials, such as industrial design clay, or more structured materials, like cardboard? What role do non-verbal cues play in the discussion of prototypes? What kind of cognitive style do the designers employ when prototyping and collaborating using different materials?

Analysing the physical, cultural and procedural context in which design work is accomplished, as well as the artefacts produced, offers an unobstructed look into design practice. The findings gained in these studies corroborated the existing literature suggesting prototypes and design discussions being pervasive aspects of collaborative design processes.

In spite of this direct view of designing, apart from the difficulties of gaining access to design studios willing to collaborate in this research, the unstructured field observation had limitations. It was, for example, hard to see how different variables could be controlled in these observed design processes in order to gather scientifically meaningful data. A different kind of method was needed to answer more specific questions.

A pilot study was conducted to test out different setups of a more controlled investigation into collaborative design processes. In eight experiments, different kinds of tasks, materials and ways of recording and analysing the data were tested. The experiments proved to be a valuable way of researching co-located design activities. The more visual approach to analysing the data obtained in the pilot study suggested a way forward for further research. In these analyses, various dimensions of the collaborative activities were scrutinised, like the rate of words or different kinds of expressions. However, they did not allow for the investigation of individual observations in more depth, especially the differences discerned in the use of the interpersonal space when using the three prototyping materials provided. In order to provide a deeper insight into the path, intensity, and location of the participants' movements, as well as their usage of space, a new method of analysis was needed.

In addition, new questions arose from the pilot studies. Analysing the type of gestures used in the Lego and sketching conditions, for example, indicated that representational gestures were used earlier when sketching. Another analysis showed that, while the rate of talk was attenuated, both participants were active in the interpersonal space when using Lego. Such observations raised questions like: How do the participants develop a shared understanding of the design solution in the design process? What role does the prototyping material play in such processes? And how does the designers' interaction with different prototyping materials inform their social behaviour? This need led to the development of the Proxemic Motion Trace Analysis PMTA. Tracing the proxemic motions of the participants and combining them with other observable forms of interaction promised to allow for deeper insights into how the designers collaboratively developed their solutions. The next chapter will take a closer look at the PMTA.

5

5 The Proxemic Motion Trace Analysis PMTA

This thesis set out to answer the research question as to *how different types of prototyping media contribute to collaborative design processes, particularly the 'quality' of verbal and non-verbal interaction*. In order to answer this question, and to guide the research, the relevant hypotheses have to be addressed: (1) different kinds of prototyping media inform qualitative aspects of social dynamics in collaborative design processes; and (2) different kinds of prototyping media inform the co-construction of knowledge in collaborative design processes.

In the practice studies conducted in the course of this thesis, the ubiquity of prototypes and importance of design discussions was shown. They also indicated that different prototyping media are used to perform specific functions in artefact-facilitated conversations. The early and rough prototypes of a hall stand, for example, were made almost entirely out of wires, while the more aesthetic and refined prototypes used later on where made out of balsa wood. To test the hypotheses, however, a different, more controlled method was needed. The previous chapter described the approach to the development of the Proxemic Motion Trace Analysis (PMTA), which offers a new method to test the hypotheses. This chapter will look at this method in more detail.

5.1 A new methodology

5.1.1 Tracing proxemic motion

Led by issues raised in the early attempts of a more visual analysis of the data gathered, the focus of the investigation shifted towards tracing the movements of the participants' hands within the interpersonal space. The question of how people make use of the physical space in the interaction with others, known as 'proxemics', did bear great significance in the experiments conducted. Not only how many times the participants interacted in a shared space between them seemed important observations to make, but also how intensive the motional activity was, where its focus was located for each participant, and what kind of patterns could be discerned. Thus, to be able to answer those questions a new methodology focusing on the use of interpersonal space was developed – the Proxemic Motion Trace Analysis (PMTA) – incorporating and extending the analysis from the pilot studies.

5.1.2 The elements of PMTA

The core of the PMTA lies in the visualisation of the proxemic motion traces (Figure 56). These traces represent the movement or inactivity of the participants hands within the interpersonal space. According to Prabhu (2010), proxemics distinguishes four categories of space: (1) public space, which is about 12 ft to 25 ft around an individual; (2) social space, which is 4 ft to 12 ft; (3) personal space, which is about 18 inches to 4 ft; and (4) intimate space, which is an area up to 18 inches. The PMTA focuses on the movements within the personal and the intimate space.

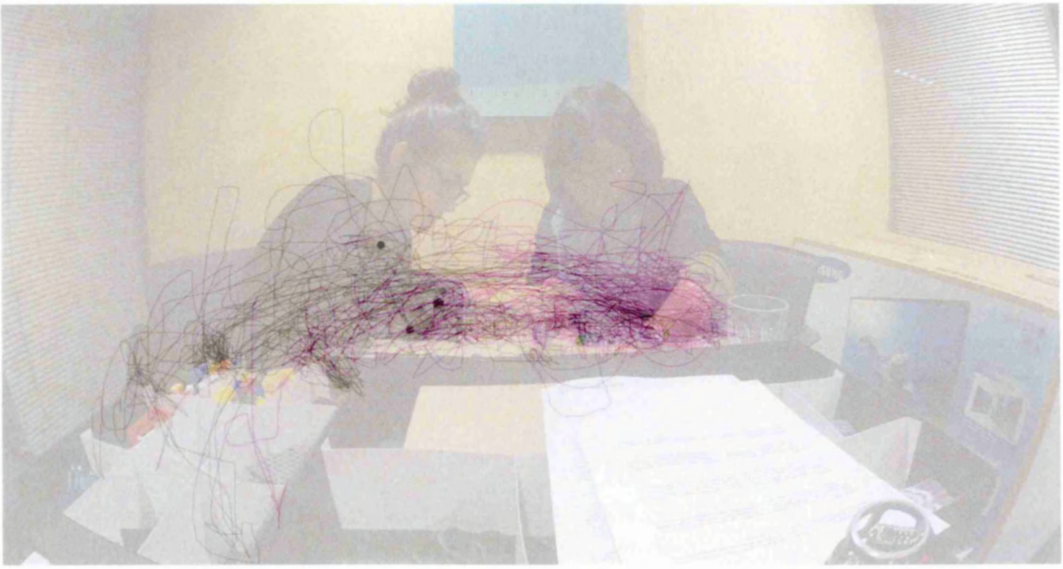


Figure 56: The recording of proxemic motion traces with PMTA in a controlled experiment.

As a methodology, however, the PMTA incorporates additional dimensions of analysis. The use of different prototyping materials, for example, was recorded for different increments of time. In addition, the location and time where and when ideas and concepts emerged during the design process were observed and annotated on the proxemic motion traces (Figure 57).

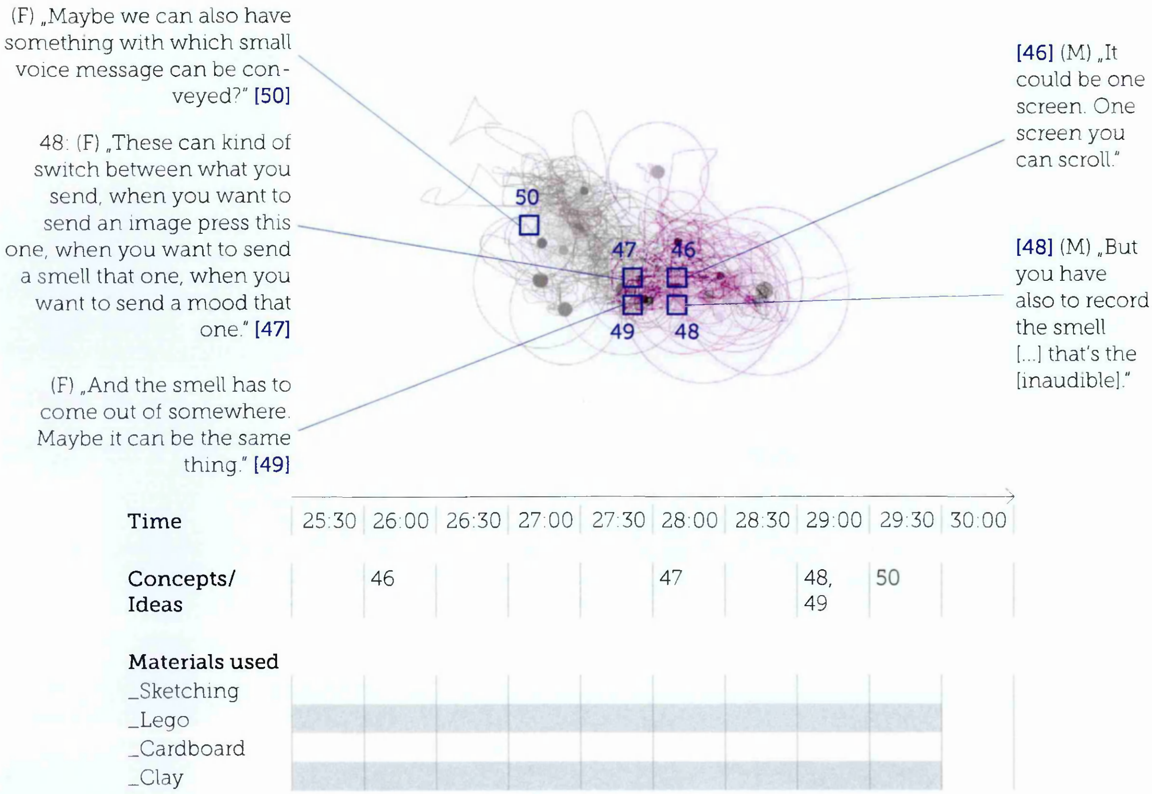


Figure 57: Analysis incorporating proxemic motion traces, emerging concepts and usage of different prototyping materials.

Marking where a specific idea emerged in the motion traces, allowed for a better discrimination of the kind of collaboration taking place and whether or not both participants interacted and contributed in the shared space. It also provided a more comprehensive picture of how the design solution emerged from the collaborative activity. Combined with the indication of what materials were used when the individual ideas were expressed, this offered a close-up inspection of each time segment analysed.

5.1.3 Set-up of experiments

The data was collected in a controlled environment, in meeting rooms at the research department at Central Saint Martins College in London. For each experiment, the same setting was used (Figure 58). The materials were provided using matching black boxes as containers. A working mat was placed on the desk in the middle of the two participants. The camera and audio devices used for the recording were placed in front of the participants using an 180-degree angle, covering the whole space used during the experiments.

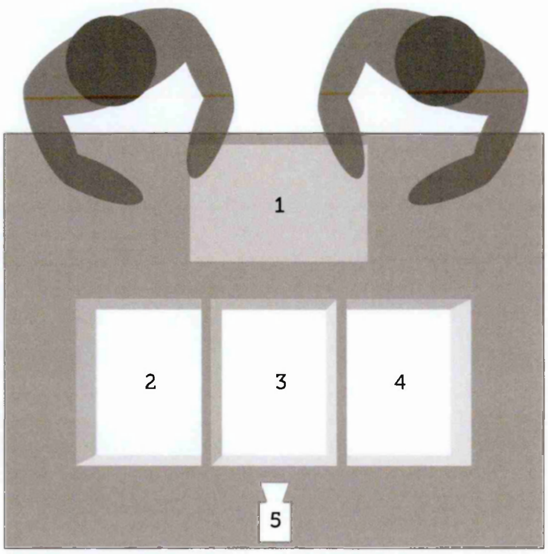


Figure 58: Experimental setup with working mat (1), material boxes (2, 3, 4), and camera (5).

Seating of participants

The two participants were always seated in the same manner, so that both participants had equal access to the working mat. Due to the way the materials were provided, it was not possible to allow for equal distances to all of the individual material boxes. Another factor to be considered was the handedness of the participants. The participants were seated without regard to whether they were right-handed or left-handed. Such a predisposition might influence the interaction with the artefact as well as between the participants themselves, and it is suggest to consider such an influence in further studies.

Number of participants

The pilot studies tested different group sizes to establish which to choose for the main study part of this thesis. The largest group size, consisting of five participants, showed that the discussion and collaboration was quickly separated into two sub-groups, working on individual design solutions. When using a set-up of three participants, one person withdrew herself from the collaboration. Using two participants provided a way to observe design discussions and collaboration in a focused way, excluding such additional dimensions of social interaction. In the pilot studies it became apparent that recruiting enough participants for the studies – as a crucial prerequisite of the research – would not be easy. Focusing on two participants allowed to conduct more experiments with fewer participants within the given time frame of the PhD programme. However, examining larger groups using PMTA would certainly be of interest and is suggested for further studies.

Recording the video and audio data

The activity was video-recorded choosing a frontal perspective. Due to restrictions in the use of the provided infrastructure, i.e. the use of the rooms and time slots assigned for the studies, the data had to be recorded relinquishing an elaborate recording set-up, in particular a top-down view. In contrast to a top-down view, the frontal perspective offered the advantage to discern facial expressions as well. Such expressions could, for example, give important indications where the focus of attention of an individual participant is located. It could also reveal whether a verbal expression is given a different or additional meaning by a bodily expression.

Recording the traces

In order to plot the hand movements of both participants occurring during the experiment, a software programme, IOGraph, was used. The programme was used to record the movements of each participant individually with movements indicated by a line, and stops plotted as dots and circles. Depending on the length of the stop, the sizes of the dots and circles increased (Figure 59). The lines represent the location in the middle of both hands when resting or when equally active. When one hand was active and the other inactive, the line followed the hand executing an action.

The two images resulting from recording each participant's movements were superimposed with an image editor and a colour code was used for better distinction of the two motion paths (Figure 60). As a result, the visualisations show proxemic motion traces of the two participants. Additionally, the motion paths of the artefacts produced during the experiment were traced.

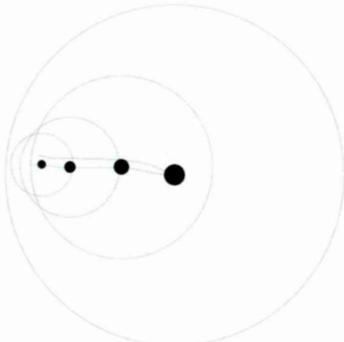


Figure 59: Dots and circles indicating stops of 3, 5, 10, and 20 seconds.

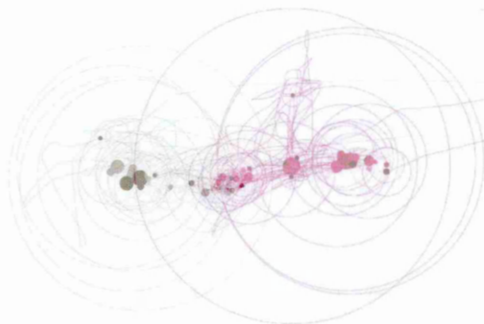


Figure 60: Combination of two motion paths of the participants' hands.

Motion trace recording rules

As the programme was originally conceived to track users' cursor movements on computer screens, its usage came with a few restrictions, which necessitated setting a few rules for recording the individual motion traces (Table 4).

PMTA Analysis Rules	
Number of participants	Each participant's hand movements are recorded separately
One hand moving	Cursor follows the hand in the middle or palm area
Two hands moving (of the same participant)	Cursor follows the hands movement in the middle between the two hands
Only one hand is visible	Cursor follows the hand visible
Both hands are visible, but only one is moving	Cursor follows the moving hand
Both hands rest in the visible area	Cursor rests in the middle of both hands
Both hands rest, but only one is visible	Cursor rests on the hand visible
Movements not related to design activity (e.g. running one's hand through one's hair)	Cursor follows hand movement

Table 4: Rules for recording motion traces for the PMTA.

One major limitation was that only one location or point could be traced at the time. This meant that the participants' hand movements could not be recorded simultaneously. Another significant limitation was the circumstance that the movements could not be recorded automatically, but had to be followed by hand (Figure 61). Obviously, these aspects of recording would inevitably lead to considerable differences in the data produced. To ensure a more congruent procedure of analysis, a set of rules was defined for recording the motion traces.

Figure 61: Recording participants' motion traces manually using IOGraph.

Variation & limits of accuracy

Although the analysis rules outlined were attentively observed, differences and variations between individual recordings of the motion traces are inevitable when generating them by hand. For as long as recording the hand movements following a predefined set of rules is not possible automatically, these variations have to be taken into account when using PMTA to analyse design processes. Thus, the accuracy with which the movements can be recorded defines the level of detail to which the data may be analysed justifiably. Figures 62 and 63 illustrate the variation – and congruency – of the same segment of motion trace analysis, done in two different instances. The example shows that in the detailed analysis there are quite a few differences in the motion traces followed and the pauses recorded. However, the overall appearance and location do not vary greatly. The general areas where most cases of activity and inactivity could be recorded remain visible and distinguishable in both figures. The overall shape of the recorded motion traces also appears to stay the same.

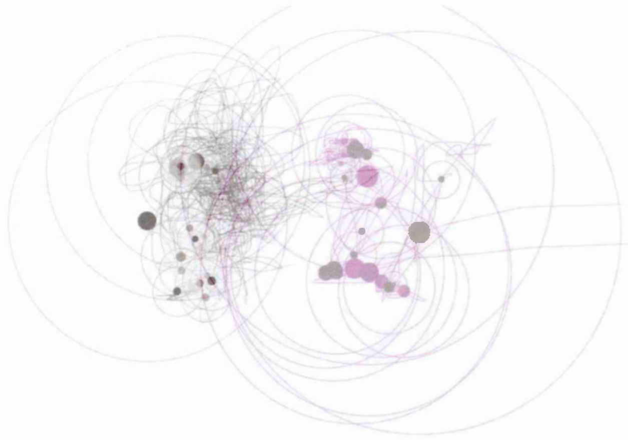


Figure 62: Sample motion trace analysis of the hand movements occurring in the first five minutes of experiment 5.

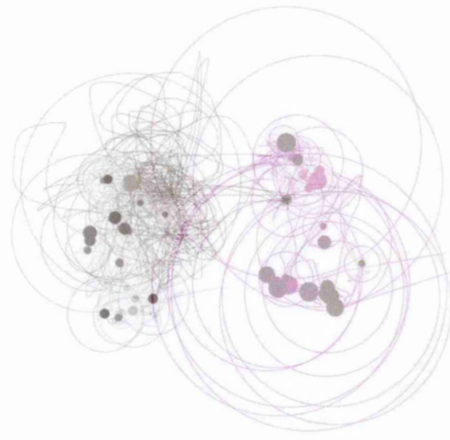


Figure 63: Sample motion trace analysis of the hand movements occurring in the same five minutes of experiment 5 produced in a different recording session.

The differences and similarities discernible in Figures 62 and 63 do imply the altitude from which the data may be analysed. The contrasting juxtaposition indicates that it seems justifiable inferring conclusions based upon the overall shape of the PMTAs and the general location of individual areas of activity and inactivity, but not based upon the location and course of individual dots and lines. Such a fine-grained analysis, however, might be justified once an automatic recording can be devised, which minimises those variances.

Adapting 'Linkography'

As a method to unveil the design process in detail, PMTA can also be combined with other methods of analysis. Linkography, for example, is a method of analysing the emergence of design moves during design processes, developed by Goldschmidt (2014) (see Chapter 3). The author describes in detail how, using the methodology, 'linkographs' may be generated. In this thesis, these linkographs have been somewhat adapted in order to allow for a more revealing combination with the PMTA visualisations. 'Linkographs' offer the opportunity to look at how individual design moves are connected with each other. In combination with the PMTA, these representations allow one to discern connections between different patterns of proxemic activity, the location of emerging ideas, the materials used and the relations of individual design moves over the duration of the design process.

While in the original linkograph depiction the design moves are all listed in an uninterrupted chronological order, the adapted representation used in this thesis allows for space between individual design moves to better visualise their affiliation to a specific time segment (Figure 64). The segments are divided into bits of five minutes each. The design moves or concepts emerging within these segments are being aligned along the PMTA visualisation of the respective segment. This has implications regarding the visual representation of individual patterns (like chunks, sawtooth tracks or web patterns), which have to be considered when analysing the modified linkographs.

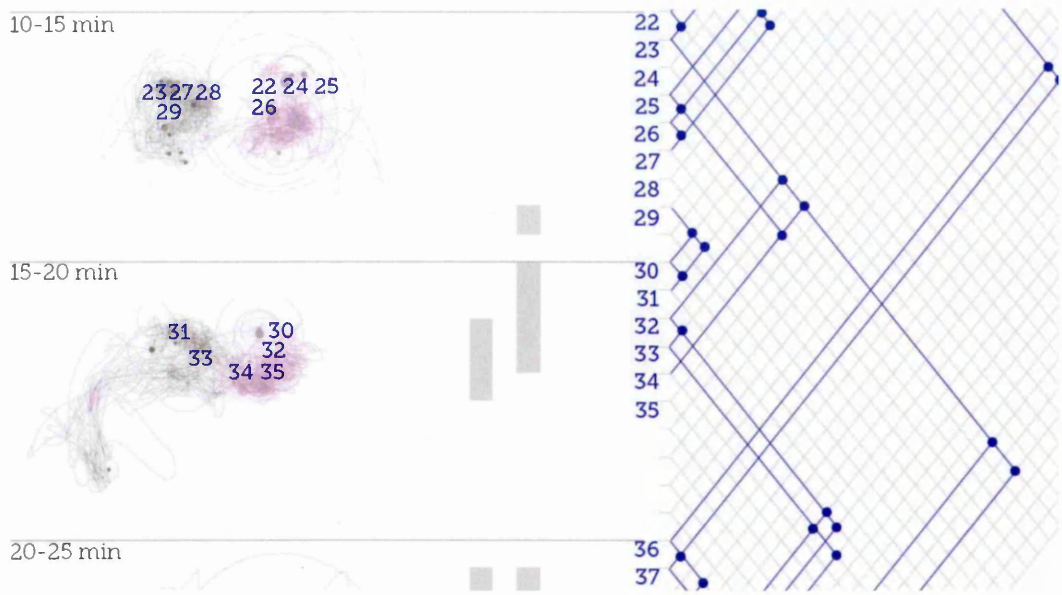


Figure 64: Adapted representation of the linkograph for better alignment with the PMTA visualisations.

Goldschmidt explicitly states the nature of design moves as any "step in the process that changes the situation" (p. 42). In order to investigate the emergence of ideas in the design process, this definition of a design move has been narrowed down, for this thesis, to design moves either suggesting an addition or alteration of an already expressed idea or concept, or proposing a new idea, concept or development.

5.1.4 Measuring design activity

Analysing the design process from multiple angles using PMTA allows the applying of measures to the collaborative design activities observed. Dillenbourg (1999) suggests that situations, interactions and processes can all be characterised as collaborative. Regarding collaborative situations, he argues that "a situation is termed 'collaborative' if peers are more or less on the same level, can perform the same actions, have a common goal and work together" (p. 7). This, according to Dillenbourg, requires some sort of symmetry of interactions – symmetries like 'symmetry of action', 'symmetry of knowledge' or 'symmetry of status'. Collaborative interactions can be characterised by the extent to which they "influence the peers' cognitive processes" (p. 8), the occurrence of 'synchronous communication' instead of 'asynchronous communication' (which would be associated with cooperation rather than collaboration), and negotiability (which implies some degree of status symmetry). As specific to collaborative processes, Dillenbourg identifies the two phenomena of 'internalisation' and 'appropriation'. The former describes a transformation of external 'tools' from a social to an intra-personal dimension. The latter denotes the reinterpretation by an individual of "his own action or utterance under the light of what his partner does or says" (p. 11), indicating a mutual influence of cognitive processes between collaborating people.

Regarding Dillenbourg's categories of situation, interaction, and process, the PMTA offers variables that can help measure the kind and degree of connectedness taking place in design processes indicative of collaborative activity (Table 5).

Characterisations according to Dillenbourg	**Variables offered by PMTA**
Symmetry of interactions & synchronous activity	Measured by evaluating the degree of symmetrical motion traces & by evaluating the degree of synchronous motional activity
Negotiability & synchronous communication	Measured by evaluating the ratio of contributed ideas/design moves
Influence of cognitive processes & appropriateness	Measured by evaluating the degree of linkage between ideas/design moves

Table 5: Variables proposed to measure characteristics of collaborative activity according to Dillenbourg (1999).

Symmetry of interactions: degree of symmetrical motion traces

Evaluating the degree to which the two participants' motion traces are symmetrical in their intensity indicates whether a symmetry of interaction took place during the observed design activity, i.e. whether both participants were more or less equally active (Figures 65-67). The symmetry of the motion traces' location provides an insight to where the participants individual actions were performed. This shows whether the locus of activity was shared between the two participants or whether their use of the interpersonal space was different. The latter would indicate that the activities occurring during the observed time period could be of a different nature.

Figure 65: Example of a very symmetrical motional activity in experiment 19 between 10–15 mintues: both, the intensity and locus of the motion traces seem quite symmetrical.

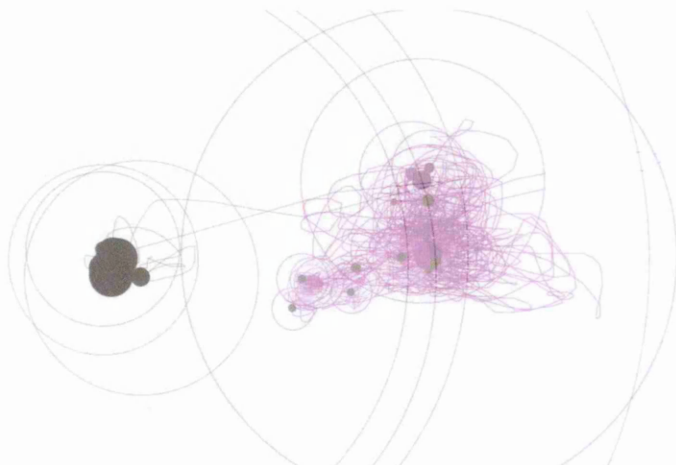


Figure 66: Example of a very asymmetrical motional activity in experiment 16 between 30–35 mintues: intensity and locus are not congruent at all.

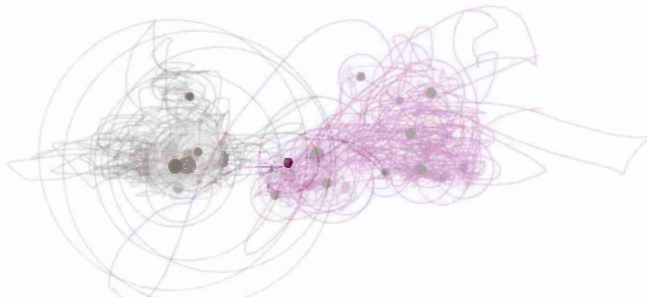


Figure 67: Example of a somewhat symmetrical motional activity in experiment 16 between 30–35 mintues: intensity and locus are a bit incongruent with the participant on the right showing slightly more motional activity and more use of the interpersonal space.

Equality of contribution: ratio of contributed ideas/design moves

Calculating the ratio between the participants' individual design moves or contributed ideas during the design process indicates the degree of negotiability and synchronous communication occurring. A strong tendency towards one of the participants suggests that one of them was either reclusive or inhibited in some way. In this case, one possible interpretation could be that an asymmetry of status or knowledge (e.g. design expertise, language barriers, etc.) was occurring. Other interpretations could be that one participant did not feel the same sense of ownership over the design solution or was simply tired. In all cases, an asymmetric form of collaboration takes place indicating a lesser degree of connectedness.

Mutuality of cognitive influence: degree of linkage between design moves

Evaluating the degree to which ideas or design moves are linked amongst each other provides an understanding as to what extent the cognitive processes have been mutually influenced by the participants, or as to what extent the participants reinterpret their actions in the light of what their collaborators do. The linkage indicates that design moves are being received and cognitively processed. The more ideas are linked, the more connected the collaborative activity may be described. The degree of linkage may be determined by analysing the number of connected design moves in the linkograph.

Coding scheme & calculation

In order to measure the connectedness of the design activities observed, according to the three dimensions described above, a simple coding scheme may be applied to attain the individual coefficients (Table 6). While the coefficients for the ratio of contributed design moves and the degree of linkage between design moves can be calculated, a more interpretative approach was used to define the coefficients for the degree of symmetrical motion traces. To that end, the PMTAs were visually analysed and categorised either as a 'symmetrical activity' with a coefficient of 3 (Figure 65), as an 'asymmetrical activity' with a coefficient of 1 (Figure 66), or as a 'somewhat symmetrical activity' with a coefficient of 2 (Figure 67). This way of measuring the connectedness of collaborative design activity is, in its present form, rather intuitive. Further research is suggested to refine the measurement in order to achieve a more objective way of obtaining the individual coefficients.

Coding Scheme for Measuring Connectedness			
	1	2	3
Degree of symmetrical motion traces & synchronous motional activity	Location and intensity of motion traces asymmetric	Location and intensity of motion traces somewhat asymmetric/symmetric	Location and intensity of motion traces symmetric
Ratio of contributed design moves	Ratio clearly in favour of one participant	Ratio somewhat in favour of one participant	Ratio equal for both participants
Degree of linkage between design moves	Individual participant's design moves show only few links and many orphan moves	Individual participant's design moves show a medium amount of links and only a few orphan moves	Individual participant's design moves show many links and almost no orphan moves

Table 6: A simple coding scheme to deduct the coefficients of the individual dimensions.

To determine the coefficients relating to the ratio of contributed design moves, a table of individual ratios is proposed (Tables 7 & 8). The highest coefficient, 3, is given to the ratio range between 1:1 to 1:0.70 indicating equal or near-equal numbers of contributions, coefficient 2 is given to ratios between 1:0.69 to 1:0.30 and coefficient 1 to ratios between 1:0.29 to 1:0.

Coefficients Assigned to Ranges of Ratios		
Coefficient '3'	**Coefficient '2'**	**Coefficient '1'**
1:1 to 1:0.70	1:0.69 to 1:0.30	1:0.29 to 1:0

Table 7: Ranges of individual ratios and their assigned coefficients.

Assignment of Coefficients to Ratios of Contributed Design Moves											
Number of Design Moves	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
0	3	1	1	1	1	1	1	1	1	1	1
1	1	3	2	2	1	1	1	1	1	1	1
2	1	2	3	2	2	2	2	1	1	1	1
3	1	2	2	3	3	2	2	1	1	1	1
4	1	1	2	3	3	3	2	2	2	2	2
5	1	1	2	2	3	3	3	3	2	2	2
6	1	1	2	2	2	3	3	3	3	2	2
7	1	1	1	2	2	3	3	3	3	3	3
8	1	1	1	2	2	2	3	3	3	3	3
9	1	1	1	1	2	2	2	3	3	3	3
10	1	1	1	1	2	2	2	3	3	3	3

Table 8: Design moves contributed by each participant and coefficients their ratios relate to.

Using the individual coefficients, the degree of connectedness for each fraction of time may be calculated (Table 9). This allows one to better discern the kinds of collaboration, i.e. the connectedness of design activities, taking place while the design process evolves.

Calculation of Degree of Connectedness per Observational Period								
	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min	30-35 min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	1	1	2	3	3	3	1	1
Ratio of contributed ideas/design moves	2	1	3	3	3	3	3	2
Degree of linkage between ideas/design moves	1	1	2	3	3	3	2	2
Degree of connectedness	**4**	**3**	**7**	**9**	**9**	**9**	**6**	**5**

Table 9: Sample calculation of connectedness for individual fractions of the design process.

The values in this example range from 3 to 9. The extreme values of 3 and 9 indicate a rather unconnected collaborative activity in case of the former, and a very close collaboration occurring in case of the latter. However, to make assumptions about the nature of the collaborative design activity measured with values between 4 and 8, a more detailed look at the individual types of collaborative design activity has to be taken.

5.1.5 Main study method

The data used in the main study of this thesis was collected and analysed in a number of quantitative and qualitative methods to look at various aspects of collaborative behaviour and their interaction, specifically (1) hand movements, (2) interpersonal space, (3) gestural type, (4) verbal rate, and (5) the use of language.

The final study design, developed from the method and findings of the pilot study, randomly allocated two designers per group, working collaboratively on a design brief using three different prototyping media: a structured material (Lego bricks), a semi-structured material (cardboard) and a non-structured material (clay). The control group was only allowed to use sketching materials for the main task. Prior to the actual experiment, the participants were informed about the experimental procedure itself and their rights as participants (using a standardised form of consent). The participants were then asked to perform a skill-building task first. This task was to build a square cube with each of the materials provided. The task was deliberately formulated in an open manner so that the participants could choose whether they want to produce a simple form or a more elaborate interpretation of a square cube as design solution. Five minutes were given for each cube. No order of materials was set, so participants could choose with which material they would start and end. They were then asked to work on the main design brief, which instructed them to develop an electronic device that would allow people to convey small gestures of loving and caring over a distance. At the end of the experiment, the participants were asked to fill out a brief questionnaire. All tasks were performed according to a predefined experiment schedule (Table 10).

Sequence/Step	Description	Duration
Briefing & Form of Consent	The participants are given the task in the form of a short, fictitious design brief. In addition, a form of consent to use the data for research purposes, with additional information of how and when consent can be withdrawn, will have to be read and signed by the participants.	5 minutes
Skill-building task 1	The participants will be first asked to perform a skill-building tasks making them familiar with the three different materials available for prototyping: a structured material (Lego), a semi-structured material (cardboard) and a non-structured material (Play-Doh). In each task the participants choose one material with which they will produce a cube.	5 minutes
Skill-building task 2	ditto	5 minutes
Skill-building task 3	ditto	5 minutes
Design task	The participants are asked to build one or more shared prototypes of their design solution according to the requirements given in the design brief.	35 minutes
Questionnaire	The participants are asked to fill out a short questionnaire to gather data related to the moderator variables.	5 minutes

Table 10: Schedule of the individual experiments.

Participants

In the controlled experiments, volunteering design students at Central Saint Martins College of Art and Design were observed. The participants were selected non-discriminatingly to their design discipline, gender, ethnic background or religious beliefs. This allowed for a diverse sample group of international as well as domestic students. Furthermore, it provided a setting in which the experiments could be conducted within a reasonable time frame. However, with the limitations given by the constrained time available as well as the geographical focus, using a truly random sample of participants was not possible. Whoever was willing to participate and was in the second or third year of study, was accepted to take part in the experiments. The students came from diverse cultural backgrounds, like the United Kingdom, Switzerland, China, Malaysia, India or the USA. This provided an interesting mix of nationalities. However, all of them represented a specific group of design students, willing and able to collaborate in an international setting. Under ideal conditions, the participants would have been randomly chosen and coupled for the experiments. In addition, not least due to financial reasons, the decision was made to recruit student designers as participants in the experiments. Each participant received £15 as compensation for taking part in this study. Many studies have focused on the observation of design students. Few have been conducted with experienced designers or even expert designers. Gaining access to experienced designers in research is often difficult – even more so when trying to conduct controlled experiments in a more laboratory-like setting. If time and financial resources had permitted, experienced designers would have been chosen as participants. However, quite a few of the participants had already been practising as designers for a few years.

As the participants were video-recorded, their anonymity could not be completely preserved. However, their names were anonymised during transcription in order to avoid any connection between their identity and their images used.

Experiment series

The main study consisted of a series of 23 controlled experiments – each comprising skill-buildings tasks and main design tasks, resulting in 99 individual design tasks – in which pairs of design students at Central Saint Martins College carried out predefined design tasks. The main differentiation regarding prototyping techniques was focused on sketching and three-dimensional prototyping media. The control group consisted of five pairs of designers carrying out the design tasks using sketching as a prototyping technique. The remaining 18 pairs performed three-dimensional prototyping with either mixed-material prototypes or single-material prototypes.

Informed by the previous pilot studies, the main working hypothesis for these experiments was that there is a significant and observable difference between three-dimensional prototyping media and sketching. More specifically, it was hypothesised that when using three-dimensional prototyping media, the degree of shared ownership and mutual collaboration would be higher than when sketching. Another hypothesis was that the degree to which the participants interacted with the artefacts – the models and sketches – would be higher when using three-dimensional prototyping media instead of sketching. Regarding the proxemic activity, the hypothesis was that participants would use the shared, interpersonal space between them more frequently and intensely when using three-dimensional prototyping media.

In the skill-building tasks, the participants were asked to produce a square cube with each of the materials provided. This allowed the isolation and calibration of prototyping media and collaboration, focusing on the specific relationship between the individual materials provided and the collaboration occurring. As tested in the pilot studies, the square cube was chosen, on the one hand, because it did not require a lot of additional explanation before the participants could start completing the task. On the other hand, building a simple form did not seem to exhaust the participants' creativity – a feature observed in the pilot studies, when participants were asked to build the highest tower possible. As one aim of the skill-building tasks was to acquaint the participants with the prototyping materials before starting the main design task, all the materials were presented in front of them in a standardised way to provide an overview (Figure 68). This was also done because it allowed one to discern possible preferences by observing what materials were chosen first.

The prototyping materials provided were presented in a standardised way in all of the experiments (Figure 68).

Figure 68: The materials were provided in a consistent way.

The main design task was characterised by more design complexity. It allowed one to focus on the roles and functions the different prototyping media play in collaborative design activities closer to the actual practice. In the experiments, some participants were free to use all the materials, while others were restricted to using only one specific prototyping medium, sketching, or only three-dimensional prototyping media. This allowed there to be a control group (with the sketching condition) as well as to observe whether the participants, if free to choose, would rely on three-dimensional prototyping media only or whether they would also use sketching, if provided. The prototyping materials used in the individual experimental settings were presented to the participants as shown in Table 11:

Experiment	Skill-Building Tasks	Main Design Task
1	Clay, Cardboard, Lego	Clay, Cardboard, Lego
2	Clay, Cardboard, Lego	Clay, Cardboard, Lego
3	Clay, Cardboard, Lego	Clay, Cardboard, Lego
4	Clay, Cardboard, Lego	Clay, Cardboard, Lego
5	Clay, Cardboard, Lego	Clay, Cardboard, Lego
6	Clay, Cardboard, Lego	Clay, Cardboard, Lego
7	Clay, Cardboard, Lego	Clay, Cardboard, Lego
8	Clay, Cardboard, Lego	Clay, Cardboard, Lego
9	Clay, Cardboard, Lego	Clay, Cardboard, Lego
10	Clay, Cardboard, Lego	Clay, Cardboard, Lego
11	Clay, Cardboard, Lego	Clay, Cardboard, Lego
12	Clay, Cardboard, Sketching	Sketching
13	Clay, Cardboard, Sketching	Sketching
14	Clay, Cardboard, Sketching	Sketching
15	Clay, Lego, Sketching	Sketching
16	Clay, Cardboard, Lego, Sketching	Sketching
17	Clay, Cardboard, Lego, Sketching	Sketching
18	Cardboard, Lego, Sketching	Sketching
19	Clay, Cardboard, Lego, Sketching	Clay, Cardboard, Lego, Sketching
20	Clay, Cardboard, Lego, Sketching	Clay, Cardboard, Lego, Sketching
21	Clay, Cardboard, Lego, Sketching	Clay, Cardboard, Lego, Sketching
22	Clay, Cardboard, Lego, Sketching	Clay, Cardboard, Lego, Sketching
23	Clay, Cardboard, Lego, Sketching	Clay, Cardboard, Lego, Sketching

Table 11: Experiments conducted in chronological order and materials provided. The experiments chosen for in-depth analyses are highlighted in grey.

From these 23 experiments, seven were chosen for in-depth analyses (experiments 1, 4, 5, 12, 16, 19, 22). They were chosen, on the one hand, according to the materials used – three experiments with three-dimensional prototyping media only, two with all prototyping media, and two with the sketching condition – and, on the other hand, because they showed different types of collaborative design activities described earlier.

After obtaining the ethics approval, the data was collected by video- and audio-recording all experiments. Furthermore, field notes and photographs of specific observations, as well as of the artefacts themselves, were taken. All experiments were carried out in three almost identical rooms with minimal equipment and decoration at Central Saint Martins College.

Questionnaire

A questionnaire, as well as a form of consent, had been filled out by all participants. In the questionnaire (see Appendix B), they were asked their gender, whether they were native English speakers or not, for how long they had studied design, how familiar they were with the other participants taking part in the experiment, and how familiar they were with the materials presented in the experiments. This information was gathered in order to be able to respond to specific questions that might arise during the analysis in regard to possible moderating variables exerting an influence on the data obtained.

5.2 Summary

This chapter described the PMTA method in more detail. It outlined how the experiments were set up, how the traces were recorded, what rules were applied when recording the participants' movements, and how the resulting visualisations can be interpreted. It also showed how motion traces can be combined with existing methods, such as Goldschmidt's (2014) linkography. As one example of how PMTA allows for analysis of collaborative design activities in a more integrated way, the chapter illustrated how the *degree of connectedness* can be analysed, by measuring the symmetry and synchronicity of motional activity (indicating the symmetry of interaction), the ratio of contributed design moves (indicating the equality of contributions), and the degree of linkage between the individual design moves (indicating the mutuality of cognitive influence). By defining the degree of connectedness using these three criteria, eight different types of collaborative design activity – from highly connected to highly unconnected – could be identified, according to the individual characteristics and combinations of the three measured dimensions. The chapter also showed how the main study of this thesis was set up, what materials were used, who participated, and why a skill-building and a main design task were given. Having outlined the method's mode of operation, the next chapter will review the results obtained using PMTA.

6

6 Analysing prototyping and interaction using PMTA

Studies into the social, collaborative and conversational aspects of designing have become increasingly popular. However, only a few have looked at the relationship between physical artefacts used in design processes and the different kinds of discussion these objects enable. Detailed analyses of design conversations and the artefacts produced during design processes (including sketches, drawings, gestures and prototypes) have been conducted in the past, though the interactive relationship between these two aspects – conversation and artefacts – has not been looked at in detail. Suggesting a general typology regarding the functions of sketches in designing as being thinking, talking, and communicating, Ferguson (1992) pointed the way towards further research about the different types of interaction between design discussions and the artefacts produced while designing.

This thesis aims to better understand the roles of different types of prototypes and how they contribute to collaborative design processes. This chapter will look at the findings obtained using PMTA as a more integrated method of analysing collaborative design activities, particularly in regard to the verbal and non-verbal interaction between the participants. In order to do so, seven selected experiments conducted in the main study at Central Saint Martins College will be presented and analysed in more depth. The experiments have been selected to provide insight into different types and degrees of connectedness in design collaboration. In a first set of analyses, the results from the skill-building tasks will be reviewed, comparing the intensity of movement, the rate of talk, the gestural types used, the conversation taking place and the emergence of concepts when using Lego and when using sketching. In the second part, a detailed analysis of the main design tasks will be presented.

6.1 A controlled investigation into prototyping and discussion

6.1.1 The effects of prototyping on verbal and non-verbal behaviour

At its beginning, this thesis looked at the role prototypes play in conversation and interaction in professional design practice, exploring specifically the amount and quality of talk enabled by different design artefacts. A much narrower and controlled focus is being applied in this chapter. The role of physical prototyping media on the verbal and non-verbal interaction between designers, who are collaborating in developing a solution to a given design task, is the focal point of this investigation. It explores how selected prototyping media influence the quality of collaborative design processes. Particularly, the types of ideas and gestures as well as the use of the interpersonal space, are being looked at closely. While the unstructured field observations revealed different types of prototypes and their importance in design discussions, they did not allow for an in-depth analysis of various aspects of the interrelations between them. Verbal and non-verbal behaviour seemed to be influenced by prototypes in the field observations, but just how they related to the artefacts used could not be discerned in detail. No direct comparison between two-dimensional and three-dimensional media could be made either. In addition, verbal and non-verbal interaction could only be observed and analysed to a very limited extent. Comparing different interactions with varying participants using different prototyping media was a need identified in these first unstructured observations. Thus, in order to gain a better understanding of the effects of prototyping on verbal and non-verbal behaviour, isolating the interrelations between prototypes and interactions seemed to be a well-advised route to follow at this point.

In the literature, a strong view is held that any practical activity, and maybe designing in particular, embodies different types of thinking and that, in achieving a specific goal, these types of thinking can interact with one another. As Lloyd, Lawson and Scott (1995) observed, certain types of thinking, for example, planning, are more amenable to verbalisation than other types, such as sketching. Echoing this observation, McNeill (2005) argues that gestures have a complex relationship with speech and that they represent "visible thinking in the form of action", a view that is also held elsewhere (Goldin-Meadow, 2003; Hostetter & Alibali, 2008; Kita & Özyürek, 2003; de Ruiter, 2000).

Past research suggests that different kinds of hand gestures elicit neural activity in regions of the brain that are also activated during the mental performance of a task, as well as language and motor imitation (Gallagher & Frith, 2004). Similarly, Lloyd (2009) observed that information about tasks represented in the visual system stimulates areas in the brain which would be active if those tasks would be actually embodied in real life situations. Summarising various studies, Lloyd concludes that "the evidence suggests that proxemic behaviour, rather than working at a largely automatic or preconscious level, is regulated by our beliefs about the agency of the other person in the social interaction" (p. 306). This might be an indication that gestures could play a key role in controlling interpersonal behaviour and interaction in design collaboration.

Further complicating the interrelation between gestures and speech is the fact that the space in which gestures occur in collaborative activity is not neutral. In identifying an important aspect of co-located design collaboration, Sweetser and Sizemore (2008) suggest that "speakers reach into the shared space to mark shared social goals and shared affect as the basis for the accompanying utterance" (p. 26). Thus, it is quite oversimplifying to see gestural movements as mere indicators of the spoken word: indeed, the reverse might even be the case. This thesis, therefore, investigates the relationship between different thinking modes in the design process more closely, with a particular interest in understanding how measures of talk in designing correlate with measures of other types of activity, such as gestures or use of space in relation to prototyping, and their mutual influence.

The next sections report the results obtained from applying the PMTA to the skill-building task experiments and main design task experiments conducted at Central Saint Martins.

6.2 Skill-building task analysis

The analysis first takes a look at the results from the skill-building tasks. These shorter and more controlled segments of the experiments conducted allow for a focused and congruent comparison of the design activities taking place. First, a look at the intensity of movements will be taken. With the use of the Proxemic Motion Trace Analysis, the participants' individual movements can be visualised and combined in order to identify whether both of them were equally active or not, as well as to reveal the location of their activities and centre of attention. In a second analysis, the rate of talk will be measured. The rate as well as the spatial zones, where the individual participants were active in, were recorded. This analysis of the data aimed to reveal whether there might be design activities that are more amenable to verbalisation and vice versa. A third look categorises the gestures occurring during the conversation into three different types. Plotted along the same timeline, these types might indicate how the designers tackled the problem at hand, i.e. whether they contemplated a solution beforehand or whether it emerged while working on the prototypes. Transcript analysis is then being used to validate or refute the observations made in the previous steps. In the last analysis, an in-depth look is being taken into the emergence of ideas and concepts during the design process. In combination with the PMTA, linkograph and transcripts, this investigation can reveal just how the design processes evolved when using different prototyping media.

6.2.1 Intensity of movement

The visual analysis of the recorded hand movements in 23 experiments shows that the interpersonal space between the two participants was used significantly more when employing a three-dimensional prototyping material compared to using sketching. A comparison of hand movements between the selected three-dimensional prototyping materials and sketching in three randomly chosen experiments is shown in Figures 69-71. A square outline indicates the interpersonal space, which was marked as the red zone in the spatial grid used (see Chapter 5). Another noticeable result is the observation that the individual participants, when using sketching, paused more in their design process. The dots and circles, indicating periods without hand movement, seem to be larger and located significantly wider away from each other when sketching than when using one of the three-dimensional prototyping materials provided: Lego, clay and cardboard.

Figure 69 illustrates the stark contrast between the proxemic motion traces produced when using Lego as prototyping medium and the sketching condition in the skill-building task of experiment 20. The two visualisations show significantly more hand movements when using Lego than when sketching. Furthermore, the participants paused for longer and more often when sketching, as indicated by the size and number of the dots and circles. The square outline indicating the location of the shared interpersonal space between the participants shows a strong difference regarding the intensity of movements taking place within this area. In terms of connectedness, the collaborative activity taking place in this example shows a *strong symmetry of interaction* when using Lego, while showing a weak symmetry in the sketching condition with the participant on the left dominating the interpersonal space.

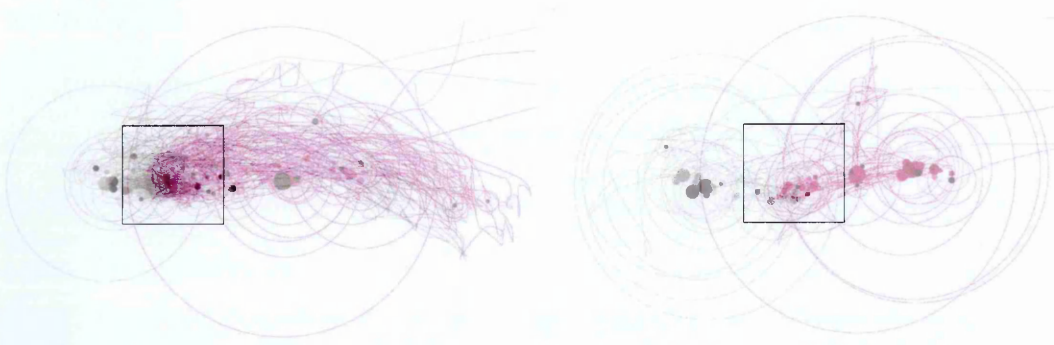


Figure 69: Comparison of the use of interpersonal space with Lego (left) and sketching (right).

Figure 70 shows a similar picture regarding the difference in the intensity of movement between clay and sketching in the skill-building tasks of experiment 12. While the symmetry of interaction appears to be a little weaker in this example when using clay, the intensity of movements and the sharedness of the interpersonal space depict an intensive activity of both participants in this area.

When using sketching, however, the low degree of intensity in the interpersonal space is evident, although the symmetry of interaction is a little stronger compared to experiment 20.

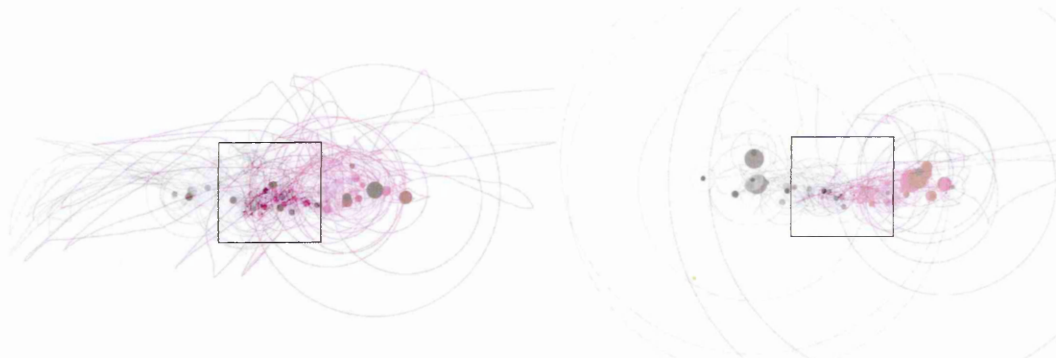


Figure 70: Comparison of use of interpersonal space with clay (left) and sketching (right).

Figure 71 depicts the visualisations of experiment 16 using cardboard and sketching. As in the previous examples, the difference between the three-dimensional prototyping medium and sketching is significant. Particularly in this experiment, when using cardboard the motion traces seem to intermingle, while the traces in the sketching condition hardly touch each other.

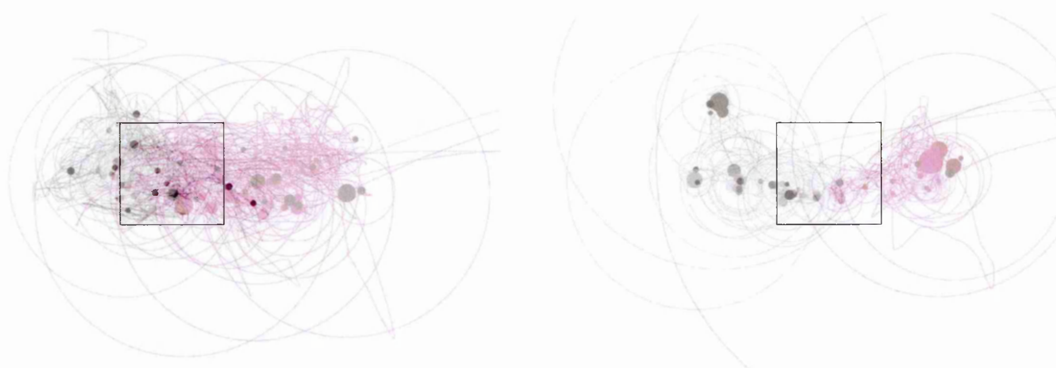


Figure 71: Comparison of use of interpersonal space with cardboard (left) and sketching (right).

The comparison of the motion trace analyses generated in the individual experiments reveals some consistent patterns. Figure 72 illustrates a limited use of the interpersonal space in the sketching experiments, with more activity taking place individually and with long and frequent phases of inactivity. A comparison of the motion traces of four randomly chosen experiments (16, 17, 20 and 22) shows the repetition of a similar pattern. Notably, all four visualisations show frequent and long phases of inactivity (indicated by the dots and circles), as well as a low motional intensity in the interpersonal spaces. In addition, they seem to be manually dominated, i.e. one participant shows more hand movements, to some degree in all experiments.

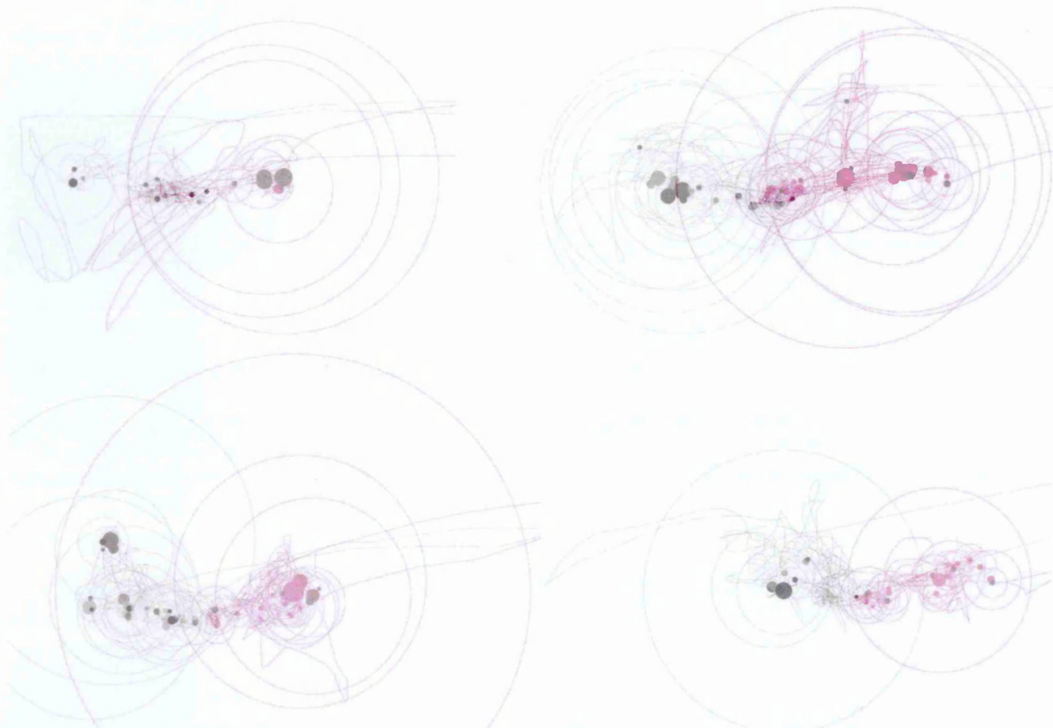


Figure 72: Proxemic motion trace analyses in the sketching condition.

Contrasting these analyses of sketching, as the control condition, to the movements recorded in the Lego, cardboard and clay experiments, a much stronger intensity in the interpersonal area can be noticed when using one of the latter. Figure 73 depicts the proxemic motion trace analysis of the same experiments using Lego as prototyping material. It reveals an intense use of the shared space between two participants, as well as the frequent use of the box containing the Lego bricks provided in the experimental set-up. In general, the participants spent more time completing the Lego task than the sketching task. Apart from the high intensity of the motional activity in these patterns, the accentuated intermingling of the individual participants' motion traces is a striking feature of these experiments.

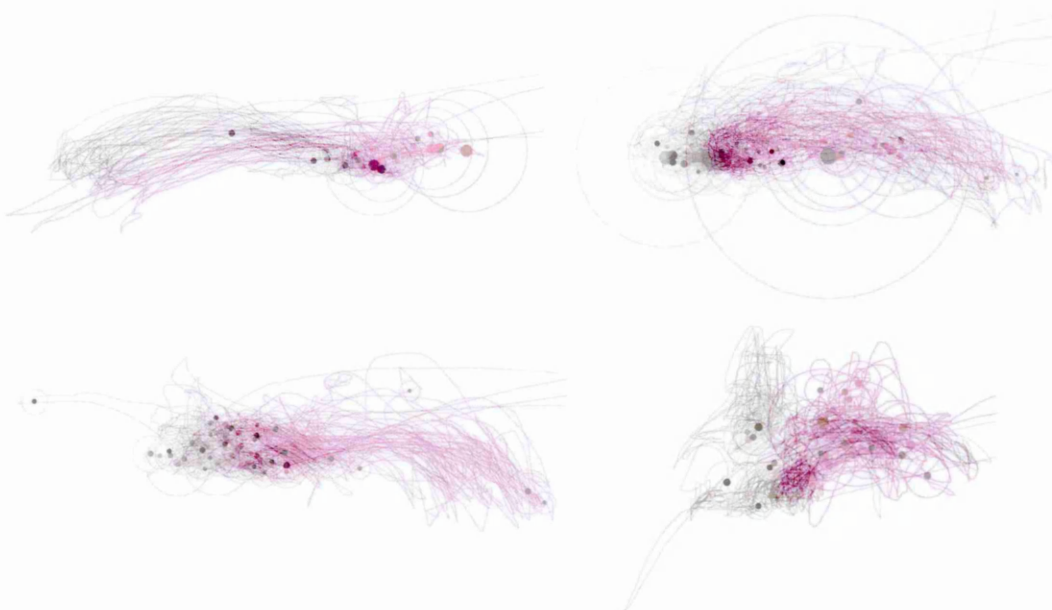


Figure 73: Proxemic motion trace analysis in the Lego condition.

A similar pattern could be recognised in the clay and cardboard conditions. Though slightly less intense, the use of the shared space between the participants was significantly higher compared to the sketching condition. In addition, the number and sizes of the dots and circles indicating phases of inactivity remained lower and smaller compared to the analyses of the sketching experiments. The cardboard condition also featured a strong use of the interpersonal space and shorter phases of inactivity, although, compared to the other three-dimensional materials, it appears to be the least intensive.

Examining the individual participants' hand movements more closely reveals differences in the use of the interpersonal space in more detail. Figure 74 clearly indicates that in the Lego condition the frequency of use of the interpersonal space of the individual participants is very high. There are dots indicating inactivities, but they tend to be short and located often within the interpersonal space.

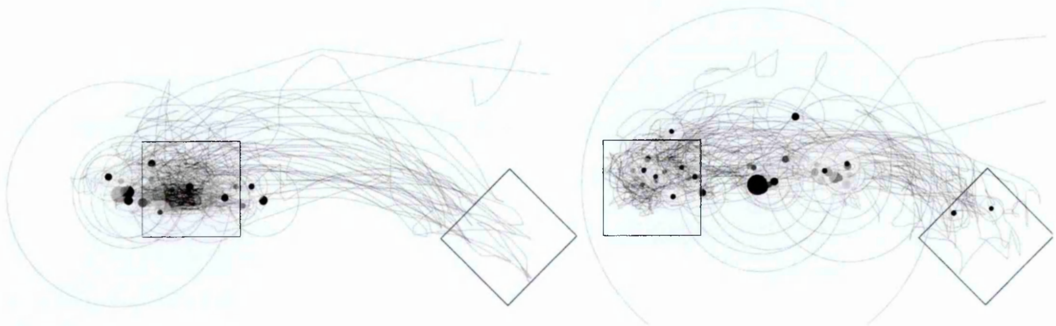


Figure 74: Individual hand movements of participants A1 (left) and A2 (right) using Lego. The square outlines indicate the location of the interpersonal space, the rhombus the location of the material box containing Lego.

When comparing this motion trace analysis to the hand movements occurring in the sketching condition, a stark difference is obvious. Figure 75, showing the individual hand movements of two participants, illustrates that there is much less activity here, more centred on the individual space, with the use of interpersonal space restricted. The activity observed in this analysis then, is less obviously collaborative, with the traces indicating more static activity.

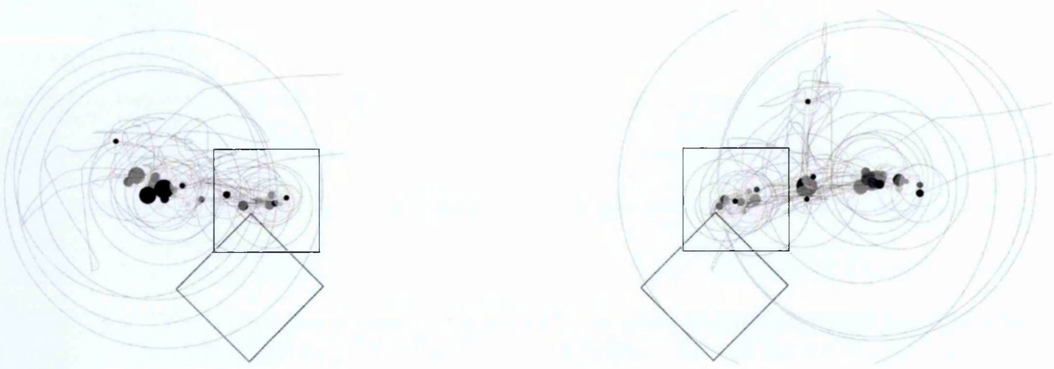


Figure 75: Individual hand movements of participants A1 (left) and A2 (right) using sketching. The square outlines indicate the location of the interpersonal space, the rhombus the location of the box containing the sketching material.

6.2.2 Emergence of concepts

Having observed differences in the way the individual materials seem to influence at which point of the design process ideas emerge, indicated by the use of different kinds of gestures in the pilot study analyses, the emergence of concepts in the design processes of twelve selected skill-building tasks was analysed in more detail. These analyses produced similar results.

When using cardboard, for example, most ideas were discussed at the beginning of the task (Figures 80-82). Notably, all ideas discussed expressed thoughts about the actual structure and production of the cube. None represented a metaphorical expression of an idea.

For the analysis of the emergence of concepts, the hand movements recorded were plotted on a timeline, showing the cumulative motion traces for each minute of the design process. The concepts emerging during the experiment were recorded in intervals of five seconds and also plotted on the same timeline, in row 4 under the motion traces. Furthermore, the origin of the concepts – for example a participant proposing a specific idea while pointing to the cube model – was recorded. The numbers in the motion traces indicate where the main focus of attention was while the idea had been put forward.

In experiment 16, using cardboard, a cumulation of emerging concepts can be observed within the first 65 seconds. After that, individual concepts are then only being suggested sporadically (Figure 76).

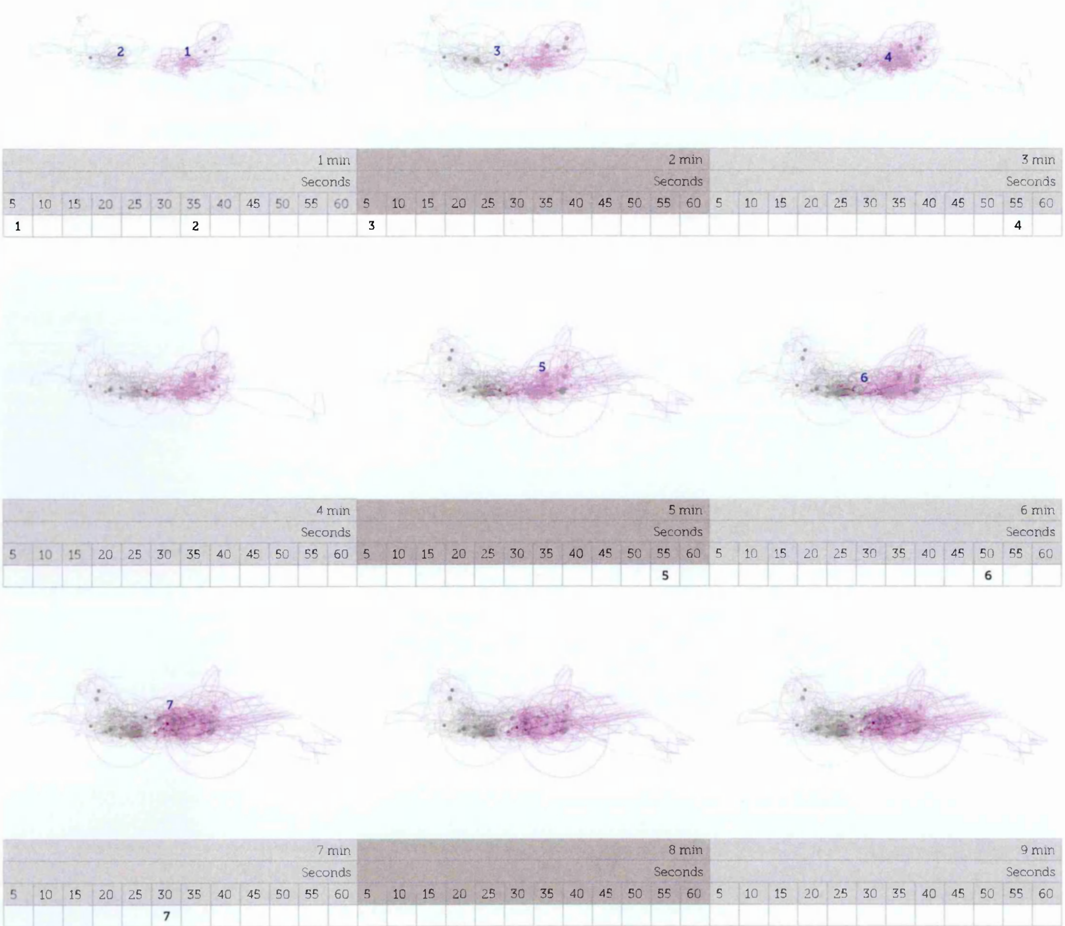


Figure 76: When using cardboard, most ideas were discussed at the beginning of the task in experiment 16.

In all three cardboard tasks analysed, work on the cube was divided, so the participants could work on their own. Working with cardboard seemed to lead the participants to work mostly within their own personal space, not using the interpersonal space between them intensively. The motion traces recorded in experiment 19 illustrate this observation well. As with the other cardboard analyses, this task shows a strong cumulation of concepts at the beginning of the design process (Figure 77). In addition, the locations of the concepts' origins seem to be within or near the interpersonal space between the participants.

											1 min												2 min												3 min
											Seconds												Seconds												Seconds
5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60
	1	2, 3			4						5					6						7													8

											4 min												5 min												6 min
											Seconds												Seconds												Seconds
5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60
9																																			

											7 min												8 min												9 min
											Seconds												Seconds												Seconds
5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60

Figure 77: When using cardboard, most ideas were discussed at the beginning of the task in experiment 19.

Experiment 22 echoes the previous observations. The motion traces of this analysis, however, seem a little distorted. This is mainly due to the location of the material box containing the cardboard, being positioned on the far right side (Figure 78).

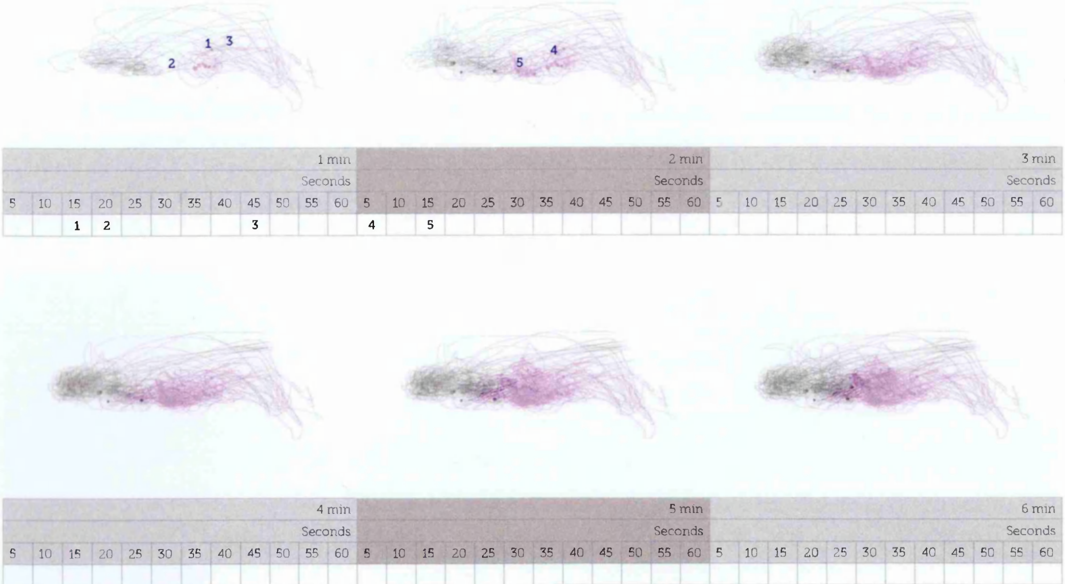


Figure 78: When using cardboard, most ideas were discussed at the beginning of the task in experiment 22.

Using clay to model the cube, the participants showed differences in the discussion of their ideas. In experiment 16, the participants expressed most ideas in the middle of the task (Figure 79).

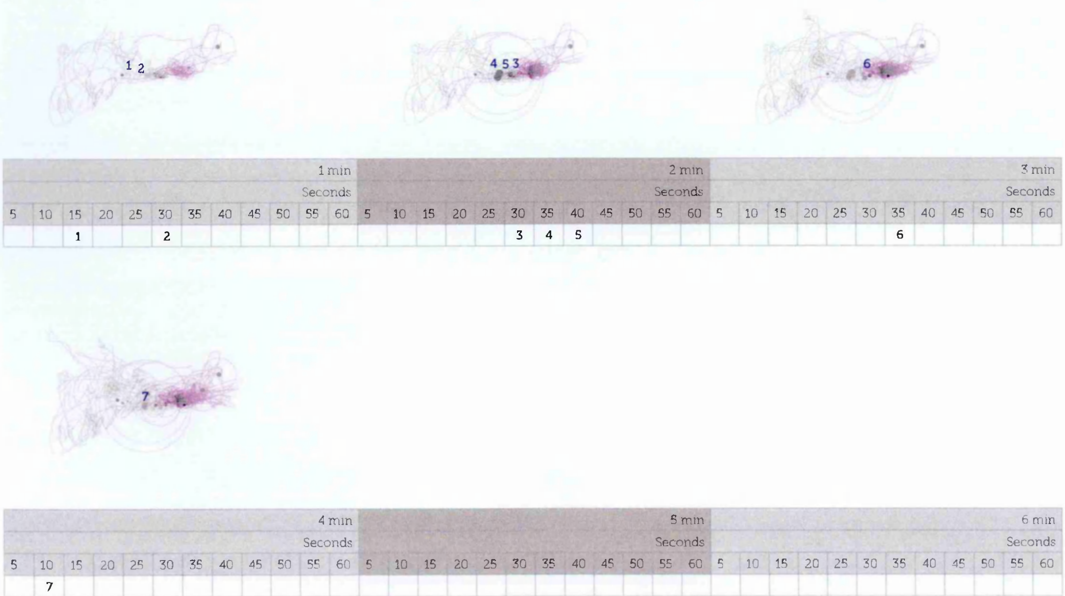


Figure 79: Using clay, ideas were expressed in the middle of the task in experiment 16.

In experiment 19, no apparent discussion of the cube's design took place (Figure 80). Only at the very end of the task did the participants discuss what name they should give their solution.

											1 min												2 min												3 min
											Seconds												Seconds												Seconds
5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60
																															1				

Figure 80: In experiment 19, using clay, no apparent discussion of design ideas took place until the very end.

In experiment 22, most ideas were discussed at the beginning of the task (Figure 81). Here the participants decided first to build four little cubes which were planned to be stuck together forming a larger one at the end. Only at the end was this idea thrown out and one little cube designated as the final solution.

											1 min												2 min												3 min
											Seconds												Seconds												Seconds
5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60
1										2			3																						

											4 min												5 min												6 min
											Seconds												Seconds												Seconds
5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60	5	10	15	20	25	30	35	40	45	50	55	60
											4																								

Figure 81: In experiment 22, using clay, most ideas were expressed at the beginning of the task.

Apart from discussing the name of the final design solution in experiment 19, all ideas expressed in the clay tasks concerned the shape, dimension and production of the cubes. The interpersonal space between the two participants was used in different ways. In experiment 16 and 19, the shared space was used quite intensively. In experiment 22, the two participants worked mostly in their own spaces.

The Lego condition offers a different picture. In the experiments using Lego as prototyping material, the participants discussed their ideas at the beginning and the end of the task in experiments 16 and 22 (Figures 82 & 83), or constantly throughout the task in experiment 19 (Figure 84).

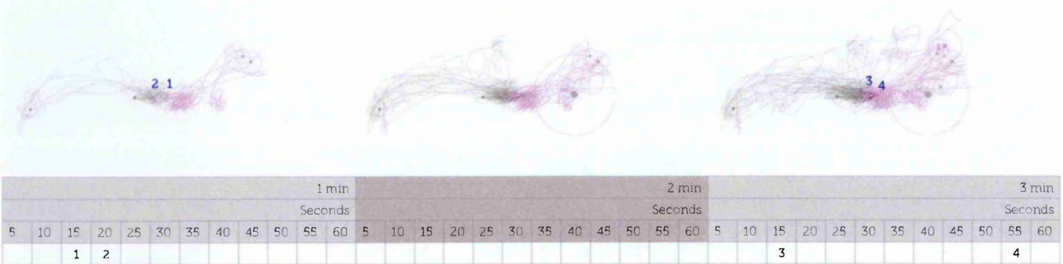


Figure 82: Discussion of design ideas at the beginning and end of the task in experiment 16 using Lego.

Notably, the experiments where the discussion of the concepts was at the beginning or end of the task, were significantly shorter (up to three minutes), than the experiment where the concepts had been discussed throughout the task (seven minutes).

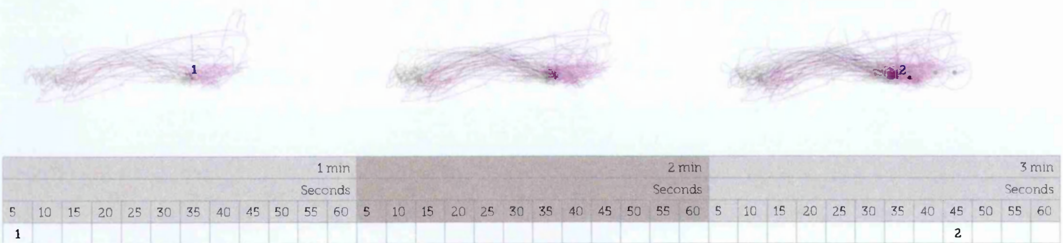


Figure 83: Discussion of design ideas at the beginning and end of the task in experiment 22 using Lego.

A common feature, however, was the notion that the participants, after agreeing to a specific design solution, worked quietly on the same cube in the middle of the interpersonal space.

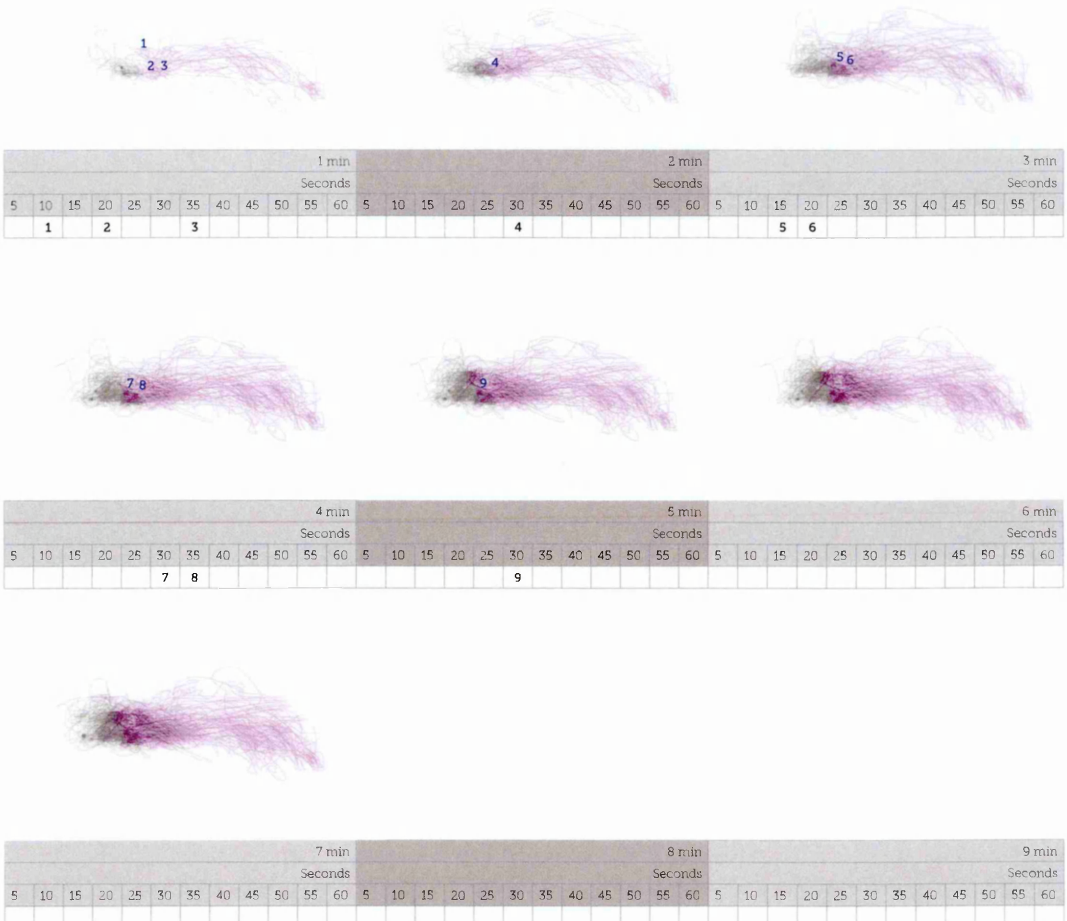


Figure 84: Discussion of design ideas throughout the task in experiment 19 using Lego.

Comparing the three-dimensional materials to the two-dimensional medium of the sketching condition, several differences seem worthwhile to notice. As previously observed, the interpersonal space between the two participants is used the least intensively when sketching. The participants paused significantly longer than when using other materials. In the examples analysed, the participants agreed upon a basic approach to accomplish the task's objective at the beginning, as in experiments 16 with the idea of a "basic cube", in experiment 19 with the idea to draw it in perspective, and in experiment 22 to divide the task into drawing the skeleton of a cube and to then colour it (Figures 85, 86 and 87). These original ideas were not altered during the experiments. In experiment 16, other ideas were expressed, like drawing it in a Cubist manner or not drawing a conventional cube. These ideas, however, were not acted upon.

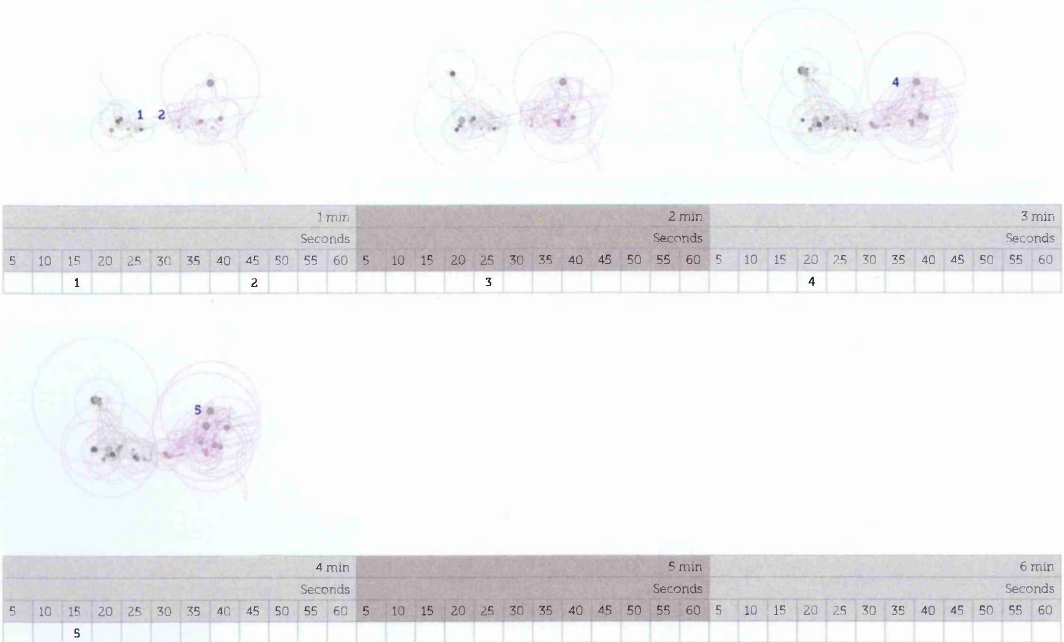


Figure 85: Experiment 16 using the sketching condition.

In experiment 19, the participants added two ideas at the end of the task, incorporating a shadow and a light source to the cube.

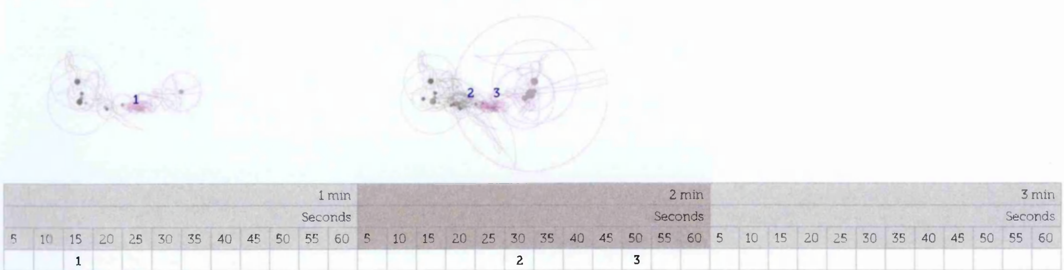


Figure 86: Experiment 19 using the sketching condition.

In experiment 22, apart from the initial discussion of the division of the task in skeleton and colouring, no ideas were discussed.

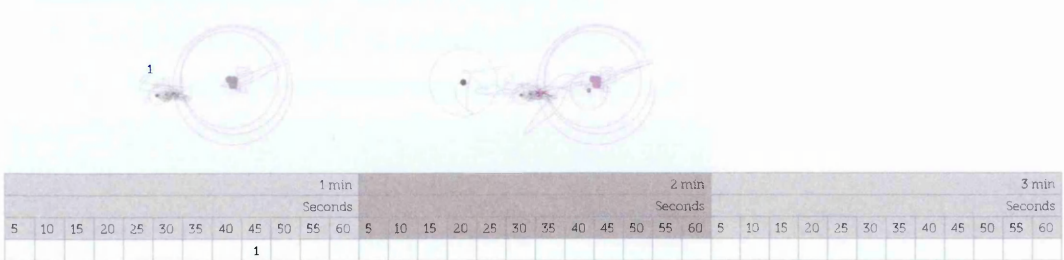


Figure 87: Experiment 22 using the sketching condition.

6.3 Main design task analysis

Through their limited scope and rather specifically formulated task, the skill-building tasks provided a focused look at the collaborative design activities being performed in the controlled experiments using individual prototyping media. However, in practice, design tasks are rarely that simple and straightforward, but much more likely to be characterised by their complexity and indeterminate nature. In addition, designers tend not to limit themselves to one specific prototyping medium, but to use the full spectrum available. Therefore, the findings from the skill-building task analyses have to be interpreted considering their limitations. The main design tasks were conducted to analyse collaborative design activities informed by more complexity. In order to provide a more complex task, the participants were asked to build an electronic device that could convey simple gestures over a distance. This required the participants to take more dimensions into account (like functionality, handling, usage or social acceptance) when developing a design solution, than in the skill-building tasks, where they could focus merely on the aesthetic form of the square cube.

From the 23 main design tasks, seven experiments were chosen for an in-depth analysis using PMTA and the adapted linkography to provide an integrated view of the observed design processes. Looking at the different kinds of data collected in the PMTAs and linkographs, it is possible to get an understanding of qualitative characteristics of the collaboration taking place during the observed design activities. One such aspect, already introduced earlier, is *connectedness*, denoting the specific characteristic of the co-located collaborative design processes observed, i.e. the symmetry of interaction, the equality of contribution and the mutuality of cognitive influence. In their combined view, these aspects of collaboration can help to measure how connected the design activity is that takes place between the participants in individual phases of the process.

In addition, for each experiment, the artefacts produced (prototypes and sketches) were depicted and analysed. By looking at the artefacts themselves, findings made in the PMTAs and linkographs could be corroborated. On the one hand, they illustrate how individual design moves were implemented in the final design solution, and, on the other hand, they reveal much about the design process itself by showing how elaborately or rudimentarily they were produced. Furthermore, they indicate how intensely the individual materials were used in the production of the artefact.

The individual tasks were selected to provide insight into different types of collaborative design activities with various degrees of connectedness observed in the experiments. Apart from providing a more integrated view of the design process, the second main focus of this thesis's research – to better understand how different types of prototyping materials inform collaborative design activities – was addressed by choosing the experiments according to the materials and combination of materials that were used. Experiment 1, for example, used all three-dimensional prototyping materials provided in their final solution. Experiment 5, in contrast, used almost exclusively clay to model the prototype. Experiments 19 and 22 used a combination of the two-dimensional sketching and three-dimensional prototyping materials, although only the latter used a sketch in their final design solution. In experiments 12 and 16, the participants used only sketching as the control condition. This selection of experiments allowed an analysis of five examples of three-dimensional prototyping – with both a combination of the prototyping materials provided, as well as a focus on one specific material – and a comparison of these with the two-dimensional sketching condition. Table 12 provides an overview of the key points of each experiment chosen for the analysis:

Experiment	Materials used in process (in order of appearance)	Materials used in final design solution (in order of importance)	Key characteristics
Experiment 1	(1) Lego (2) Clay (3) Cardboard	(1) Lego (2) Clay (3) Cardboard	Using all three-dimensional prototyping media, a *symmetry of interaction* was observed
Experiment 4	(1) Clay (2) Lego (3) Cardboard	(1) Lego (2) Clay (3) Cardboard	Using three-dimensional prototyping media from the start, a very productive *individual but connected collaboration* was observed
Experiment 5	(1) Clay (2) Lego	(1) Clay (2) Lego	Using clay and Lego after a long discussion without prototyping media, a *thorough investigative collaboration* was observed
Experiment 12	(1) Sketching	(1) Sketching	Using only sketching, a collaboration characterised by an *increasing degree of separateness* was observed
Experiment 16	(1) Sketching	(1) Sketching	Using only sketching, a *separated collaboration* was observed
Experiment 19	(1) Sketching (2) Clay	(1) Clay (2) Cardboard	Using first sketching and then clay, a *switch from a separated to a connected collaboration* was observed
Experiment 22	(1) Cardboard (2) Sketching (3) Lego (4) Clay	(1) Cardboard (2) Lego (3) Clay	Using all prototyping media, a *connected collaboration* was observed

Table 12: Overview of the selected experiments' key characteristics.

As a main similarity, all the experiments in which three-dimensional prototyping media were used showed collaborative design activities that could be described as *highly connected*. In the two experiments analysed for their use of the sketching condition, this was only the case in one experiment, with the notable difference that the collaboration changed from *highly connected* to a *disconnected and dominated but active* type of collaboration. This observation might be significant and potentially a rewarding subject for an in-depth investigation.

The experiments analysed in this chapter will be presented in the order listed in Table 14. The first three experiments (1, 4 and 5) will provide an insight into collaborative design processes informed by three-dimensional materials. They show how the design process is informed when using a combination of three-dimensional prototyping media (experiments 1 & 4), and when focusing almost exclusively on one material (experiment 5). To contrast these observations, the two experiments featuring the sketching condition will be presented (experiments 12 & 16). These show how the design process is informed when restricted to using only two-dimensional sketching. The experiments 19 and 22 will then provide more insight into the design processes in which a combination of sketching and three-dimensional prototyping is applied.

6.3.1 Experiment 1: symmetric collaboration

Experiment 1, where the participants used only three-dimensional prototyping media, could be described as a good example of a symmetric collaboration. Throughout the design process both designers contributed in equal measure to the design solution in terms of design moves and motional activity (Figure 92). Overall, the motion traces share a somewhat congruent intensity. Regarding the symmetry of movements, the participant on the right side tends to use more space. However, this might be due to the location of the materials boxes. For example, Lego, which is being used heavily in this design task, produces many motion traces recording the participants picking out individual bricks and elements throughout the design task. In contrast, with taking out the sketch pad and pencils, sketching often produces only very few motion traces. With the Lego box being located on the far right side, the interpretation lends itself that the participant sitting next to it was picking out the bricks while the other did not use the box often. Thus, taking this circumstance into account, the pattern of the motion traces can be described as rather symmetric.

Another observation worth noticing is to be seen once the participants start using the prototyping materials after around ten minutes. While the locus of activities is split into two areas, one within each participant's personal space, after starting to use the materials they seem to converge rather quickly. The two PMTAs for minutes 5-10 and for minutes 10-15 illustrate this observation quite explicitly. In the first, the participants' hand movements are located within their personal space, in the latter, the movements can be recorded being much closer together.

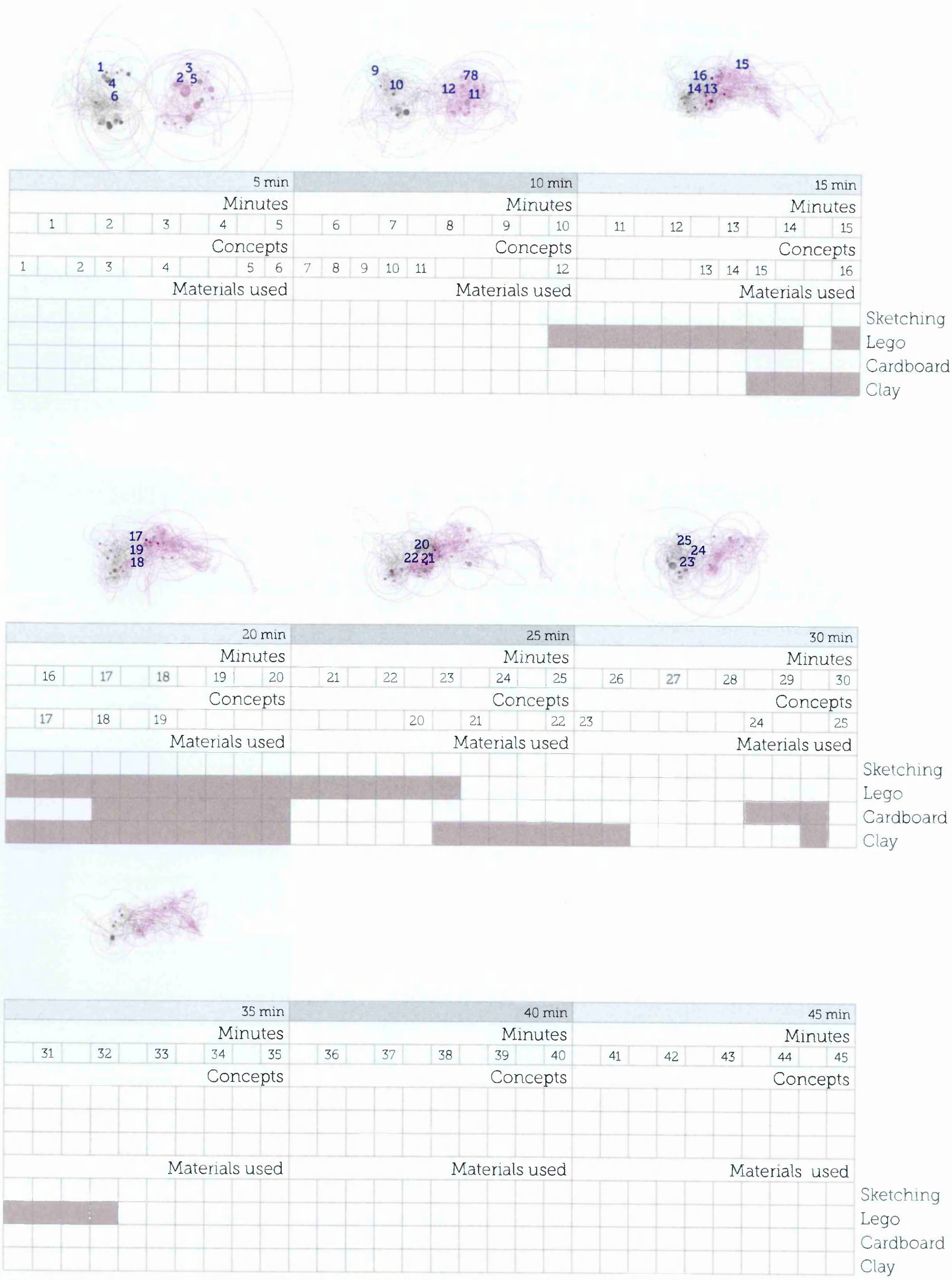
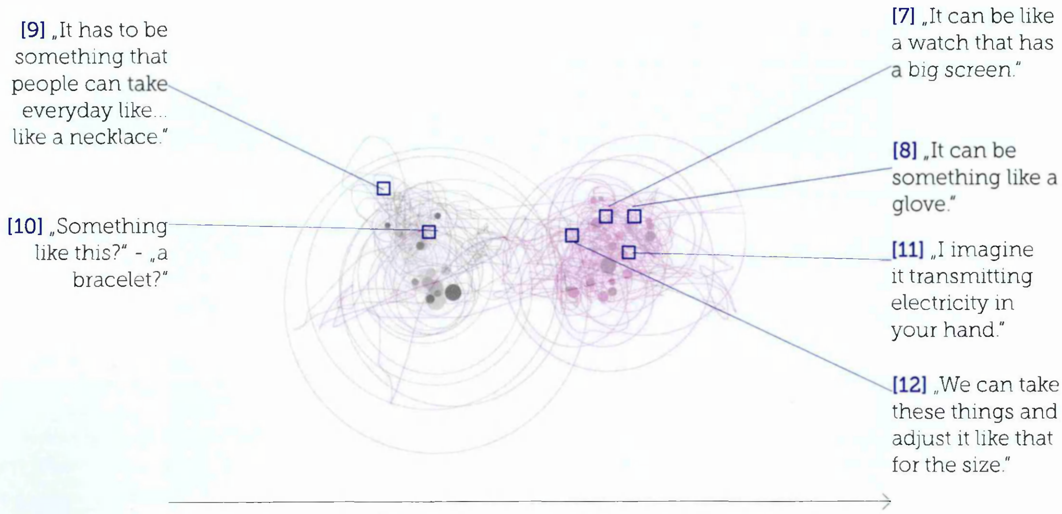


Figure 88: Emergence of ideas and concepts in experiment 1.

The participants spend quite a significant portion of their time brainstorming different ideas, without using any material at all. Only after ten minutes is Lego being used. The designers first explore different ideas without sticking too much to them (Figures 89 & 90). Functional requirements and aspects, like the portability of the device or individual features like lighting up, are being discussed simultaneously with possible solutions. From early on, a common understanding was reached regarding the final solution being portable.

Figure 89: Design moves occurring between minutes 0-5 of experiment 1.

Having implicitly agreed upon the requirement of portability, the designers brainstorm around different forms possible to address this issue. The ideas of a necklace, bracelet, glove and watch are being proposed. Simultaneously, different functional aspects are being explored, such as the device being able to transmit electricity or the adjustment of the size (Figure 90).



Time	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00
Concepts/ Ideas	7	8	9	10	11					12
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 90: Design moves occurring between minutes 5-10 of experiment 1.

Interestingly, the two participants move on developing their solution without explicitly deciding on any one of the ideas expressed. The decision appears to be made on a non-verbalised level. Obviously, starting at ten minutes into the experiment, the participants are working on a model first using Lego, adding clay later on (Figure 91). Significantly, the nature of design moves or ideas contributed changed. During the brainstorming phase, most ideas seem to have been some sort of outside reference, like a dress, a bracelet or a glove. Once working with the material, the contributions are much more focused on the functional and aesthetic aspects of the solution.

The segments depicted in Figures 90 & 91, illustrate another observation. While using Lego as a prototyping material, the participants design moves revolved around functional aspects, like adjusting the size (design move 12), a small person appearing talking to the user (design move 13), and connecting to WiFi (design move 14). As soon as clay is being used, the contributions concerned aesthetic attributes of the design solution, like a more organic shape (design move 15) and choosing the colour (design move 16).

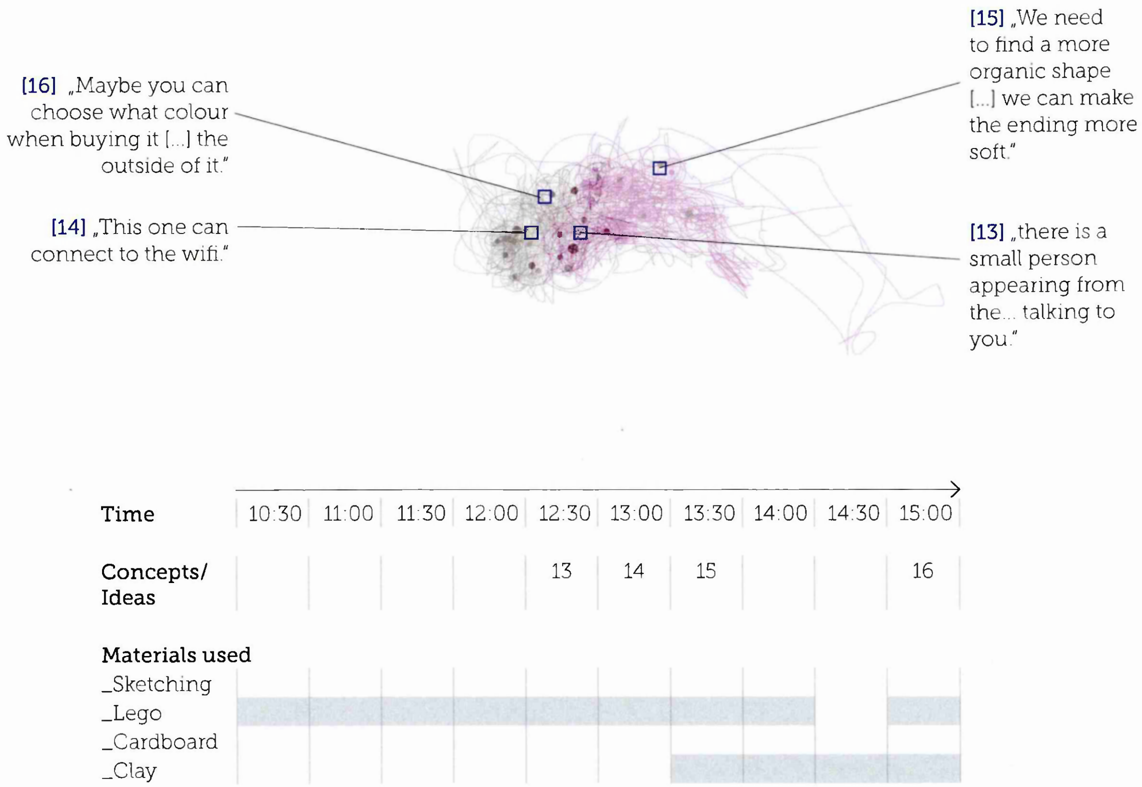


Figure 91: Design moves occurring between minutes 10-15 of experiment 1.

Figure 92 further consolidates this observation, with the use of all three-dimensional prototyping media used and the intensity of the motional activity high for both participants.

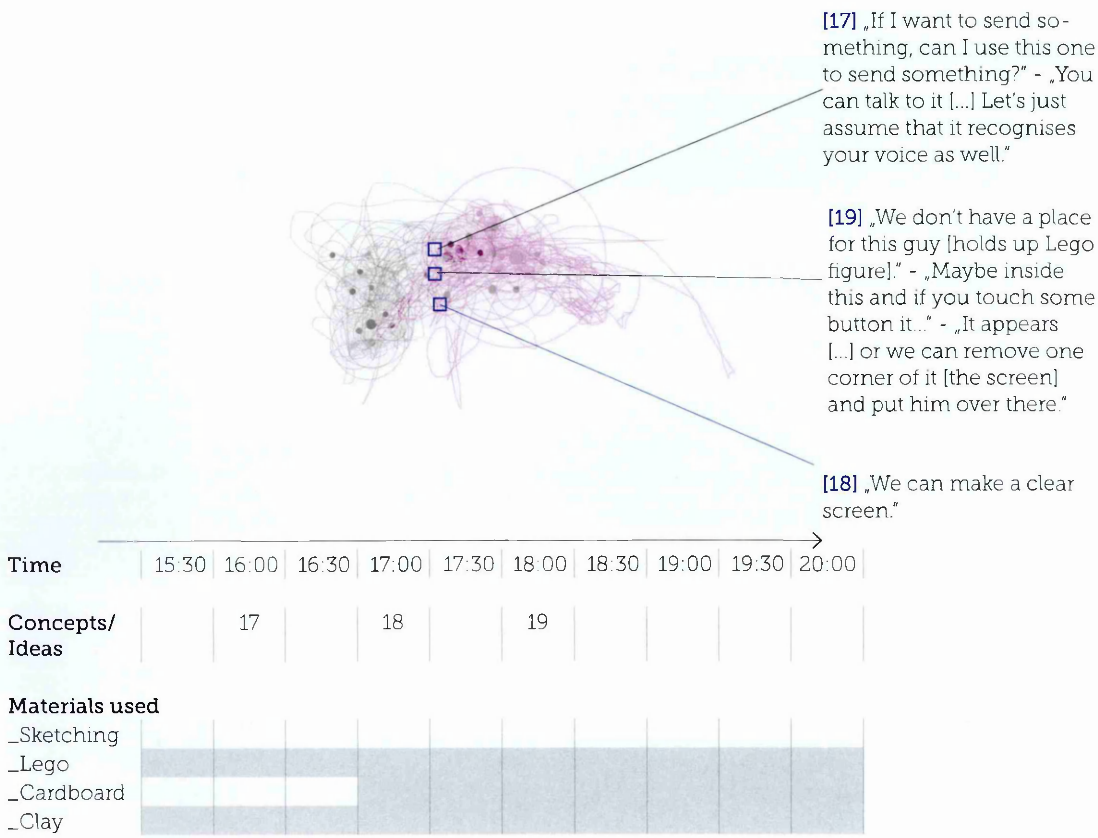


Figure 92: Design moves occurring between minutes 15-20 of experiment 1.

While the contributions by the individual participants seem to be rather congruent in their number, another observation supports the interpretation of a mutually connected design activity taking place in this experiment. Figure 93 shows three design moves proposed by the designers. While design move 21 is a rather straightforward statement regarding some new requirements, design moves 20 and 22 indicate a rather close and symmetric collaboration. In move 20, one participant asks, "How do you connect it to your computer? You connect it here?" This is a design move inviting the other participant directly to contribute one's thoughts for a specific feature of the design solution. In addition, design move 22 occurs within a context of symmetric collaboration. Occurring in the middle of the interpersonal space between the participants, like design moves 20 and 21, the suggestion of incorporating different kinds of buttons is taken up by the other participant immediately by specifying the individual functions. This indicates a kind of design collaboration that is not inhibited or distorted by asymmetric status, knowledge or engagement of the two participants.

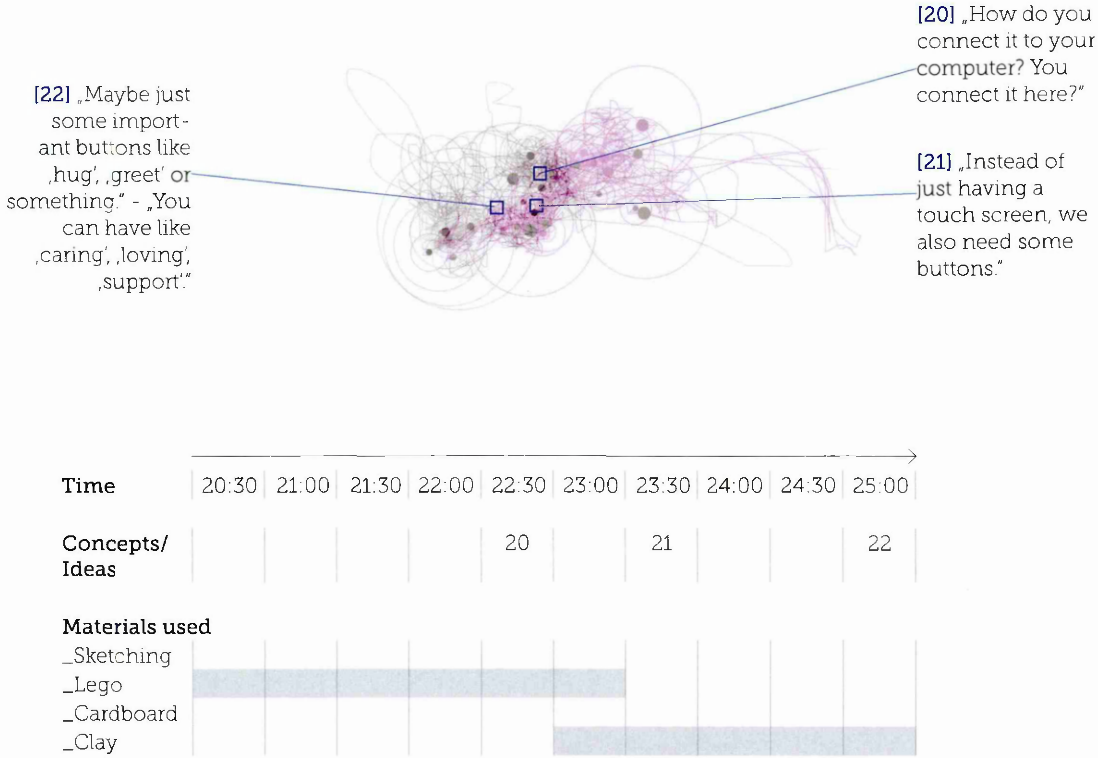


Figure 93: Design moves occurring between minutes 20-25 of experiment 1.

In figure 94 one participants is contributing all the design moves, suggesting improvements to the design solution.

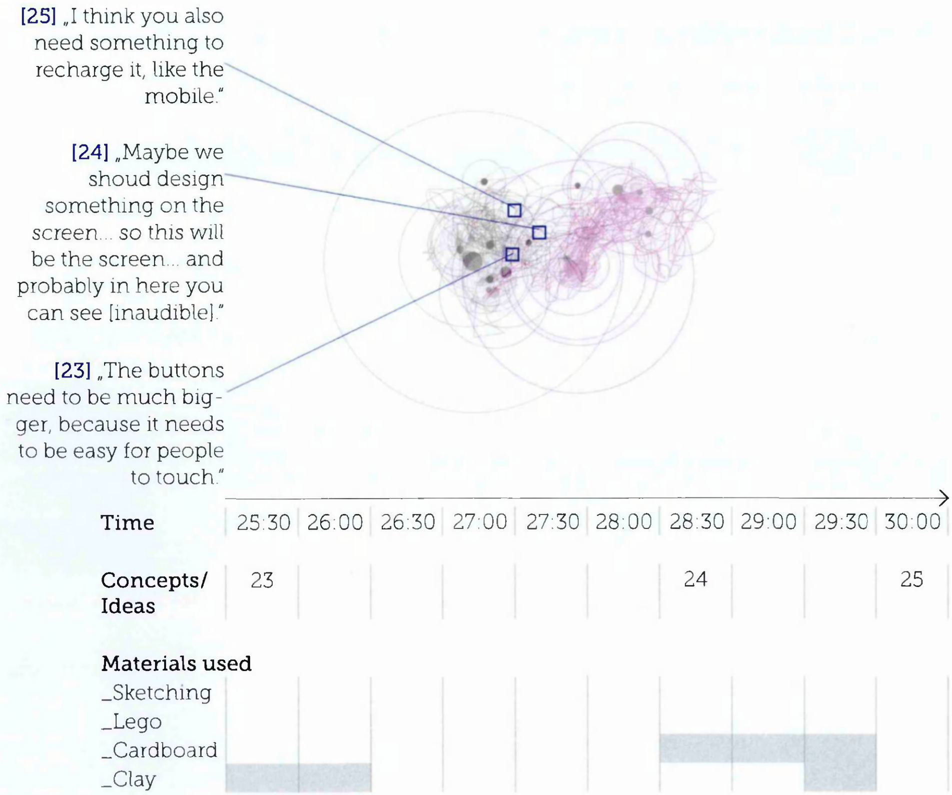


Figure 94: Design moves occurring between minutes 25-30 of experiment 1.

In the final segment of this experiment (figure 95), no design moves were proposed. The design solution seems to be completed in minute 22.

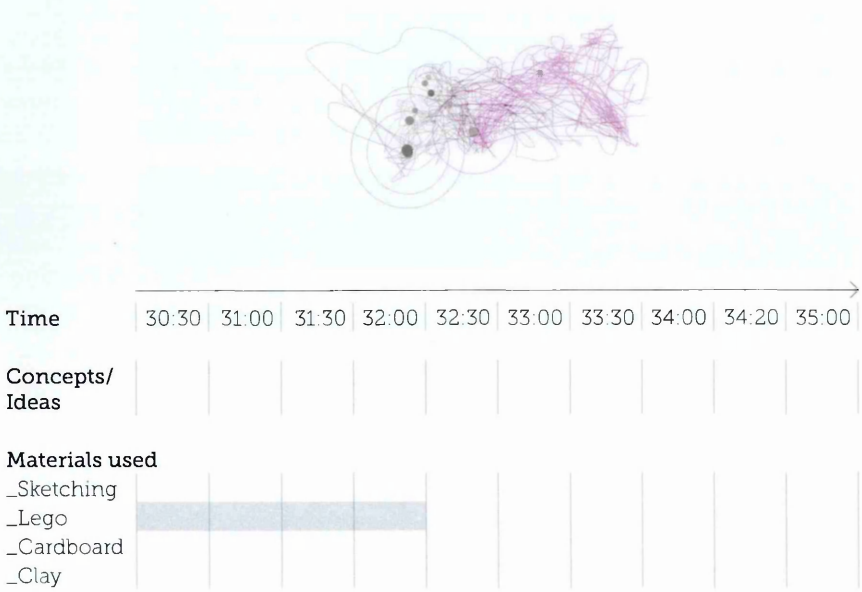


Figure 95: Design moves occurring between minutes 30-35 of experiment 1

Linkograph

The linkograph of experiment 1 shows, not surprisingly, several orphan moves within the brainstorming phase of the design process (Figure 96). The very first move, however, proposing a 'WiFi dress', has a relatively long link span, indicating its importance. The idea of integrating a WiFi functionality into the design solution appears to have been a concern of one of the participants, as it has been taken up again in the third segment (minutes 10-15) in design move 14. However, it is subsequently not developed further, indicating that the participant did not fixate on this particular idea throughout the process.

Another, seemingly more important link span or series of link spans, is to be discerned between the moves 7, 18 and 23. These moves spread over almost the entire design process. In these individual contributions, the idea of a screen incorporated in the design solution is being proposed, explored and defined, indicating this to be a prominent feature of the final design solution.

Regarding observable patterns, no significant emphasis occurred. A web pattern can somewhat be discerned, indicating passages of thorough inquiry into a specific design issue. Interestingly, no strong sawtooth pattern, indicating linear thinking, can be observed. While starting to work on an implicitly agreed upon design solution ten minutes into the design process and progressing in developing this solution throughout, the focus or the holistic perspective has been preserved by the participants.

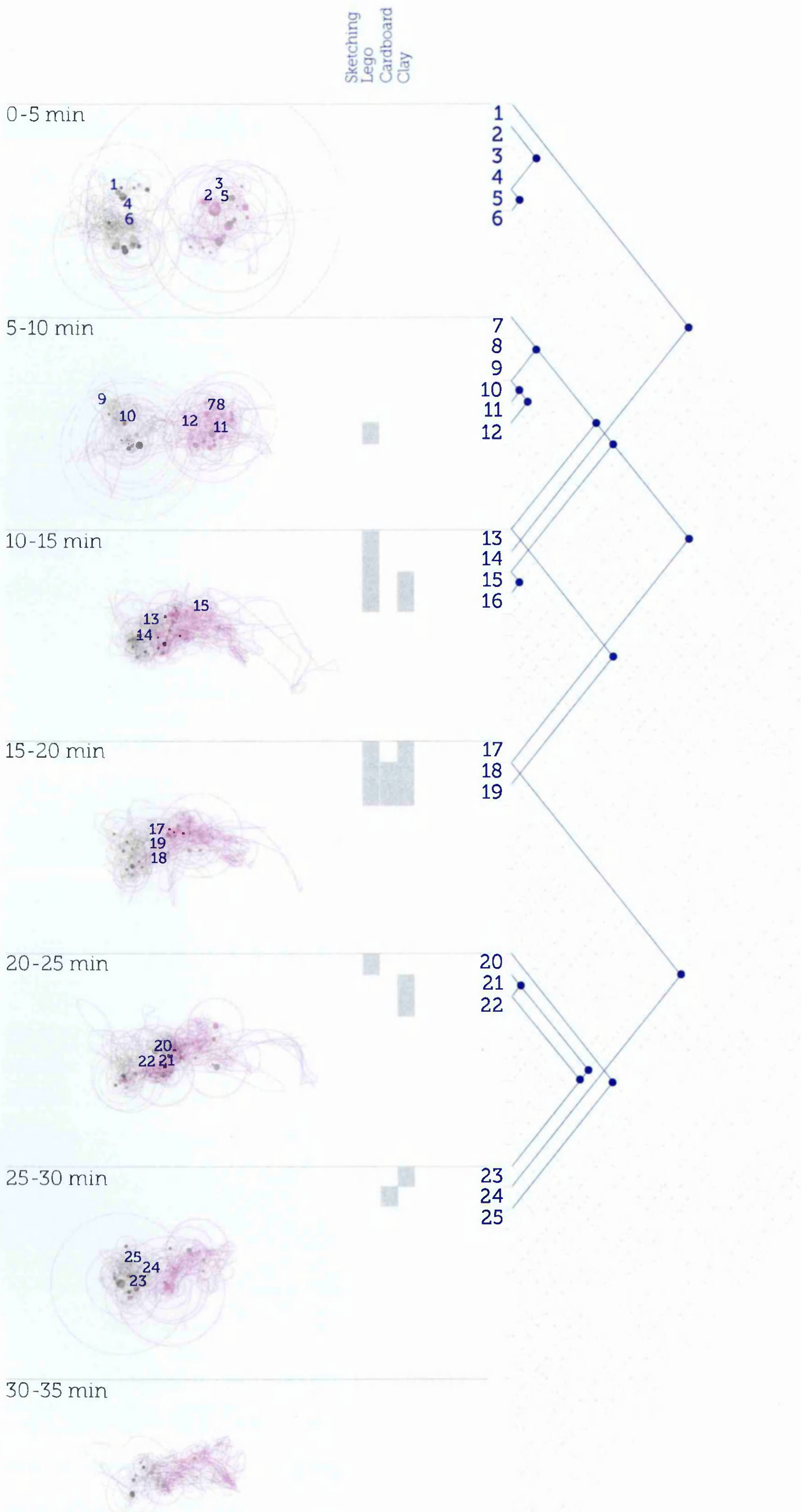


Figure 96: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 1.

Artefacts produced

The prototype produced appears to reflect the symmetric nature of the collaboration in this experiment (Figure 97). The design solution is quite detailed in regard to the device's functionality, indicating that both participants worked in the same design direction.

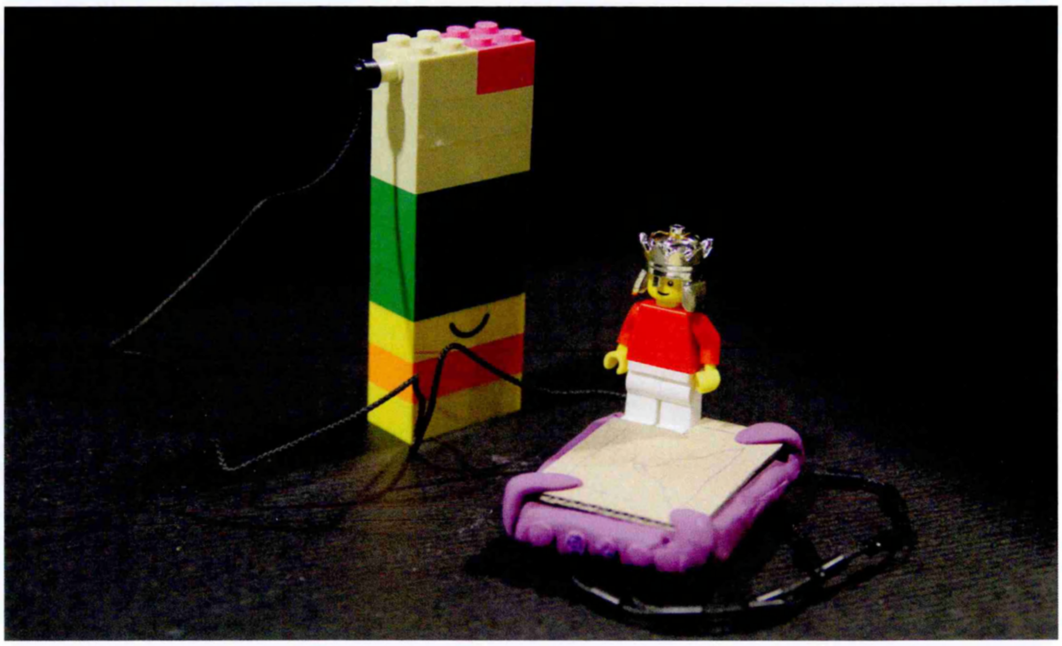


Figure 97: Prototype of the device made of Lego, clay and cardboard.

Connectedness

Measuring the connectedness of the collaborative design activities in experiment 1, a slightly inconsistent picture can be seen (Figure 98), with scores ranging from the median value of 6 to the maximum of 9. The lowest value occurs in the middle of the process, with the participants showing symmetrical motional activity, but the contribution of design moves is biased strongly towards one of them. During the brainstorming phase in the first two segments, which is also being indicated by the two separated patterns of the motional activity, both participants seem to be engaged somewhat equally in the process. The highest value of 9 was calculated for segment 3. The PMTA of this segment indicates that collaborative work has moved to the interpersonal space right between the two participants. Overall, the design activity occurring shows a high degree of connectedness. This dropped off a little in segments 2 and 4 with a value of 6. Here, although the motional activity is equal, the ratio of contributed design moves is clearly biased. In the very next segments, 3 and 5 respectively, however, the collaborative design activity changed back to a high degree of connectedness. This picture repeats itself in the next few segments, with both participants still being engaged somewhat equally in the design process. In the very last segment no design moves were proposed by neither of the participants, while both showed more or less equal motional activity.

Experiment 1 | *Symmetric Collaboration*

Degree of Connectedness per Observational Segment

	0-5 Min	5-10 Min	10-15 Min	15-20 Min	20-25 Min	25-30 Min	30-35 Min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	3	3	3	3	3	3	3	-
Ratio of contributed ideas/design moves	3	1	3	1	2	1	3	-
Degree of linkage between ideas/design moves	2	2	3	2	3	3	1	-
Degree of connectedness	**8**	**6**	**9**	**6**	**8**	**7**	**7**	**-**

(Lowest value: 3, highest value: 9)

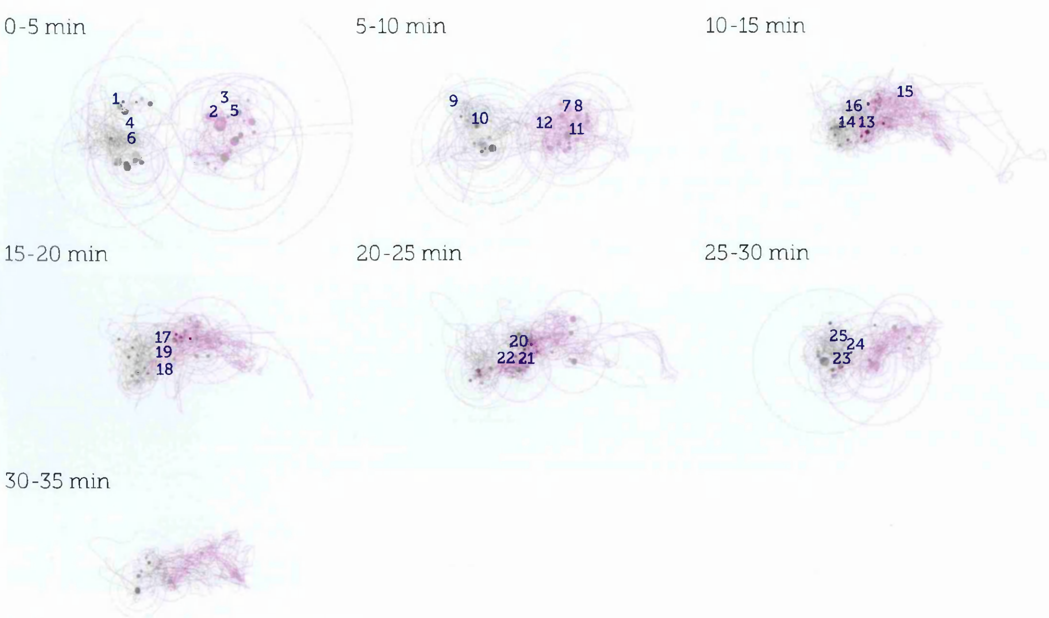


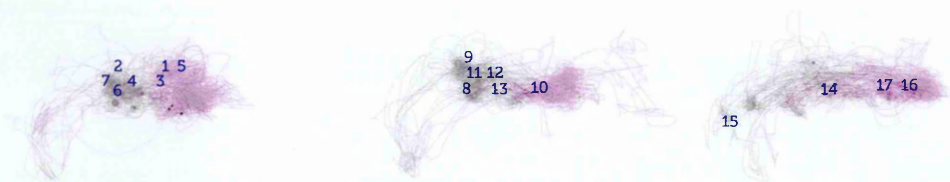
Figure 98: Evaluation matrix for the degree of connectedness and PMTAs of the individual phases of experiment 1.

Summary of experiment 1

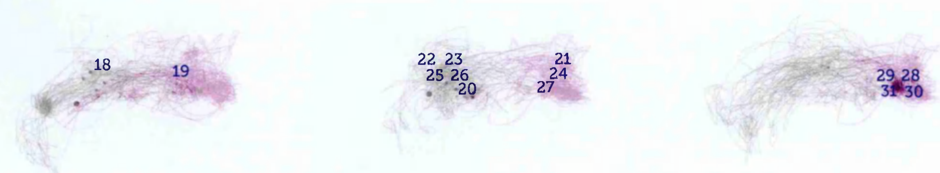
The design activity observed in this example can be described as symmetric collaboration. The motional activities of the participants were congruent in their intensity throughout the experiment, showing the maximum score in each 5-minute segment analysed. Notably, the connectedness of the collaboration could also be identified in the types of verbal expressions, with instances where one participant would invite the other to contribute their thoughts on a specific feature of the design solution. Once starting to use the three-dimensional materials, the motional activity began to converge in the shared space between the participants. Using the materials, the participants started working on the design solution without verbally agreeing on a specific design direction. This reflects the contrasting observation made in the linkograph analysis, where most orphan moves – indicating that the design idea was not followed upon – appeared before the prototyping activity in the brainstorming phase. While prototyping, the conversation was mainly concerned with functional aspects when using Lego, and aesthetic aspects when using clay. In this experiment, the participants used predominantly Lego and clay as prototyping media. The next example looks at a different kind of collaborative activity taking place while using the same materials.

6.3.2 Experiment 4: connected individual collaboration

Experiment 4 is an example of a connected individual collaboration, with the participants using the same materials as in experiment 1. In contrast to the former, however, in this example the participants started using three-dimensional prototyping media right from the beginning of the design process. The first material chosen, after around 30 seconds, was clay, which was soon combined with Lego after two minutes. The seemingly asymmetric shapes of the participants' individual motion traces can to a large degree be attributed to the location of the boxes containing the materials (Figure 99). In this instance, the Lego box was positioned on the left side, resulting in more motion traces leading to the box generated by the participant on the left.



	5 min										10 min										15 min									
Minutes		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15
Concepts	1	2		3, 4	5, 6	7					8		9	10	11	12				13				14		15		16		17
Materials used: Sketching																														
Lego																														
Cardboard																														
Clay																														



	20 min										25 min										30 min									
Minutes		16		17		18		19		20		21		22		23		24		25		26		27		28		29		30
Concepts					18	19							20			21	22	23, 24	25, 26	27		28, 29				30, 31				
Materials used: Sketching																														
Lego																														
Cardboard																														
Clay																														

Figure 99: Emergence of ideas and concepts in experiment 4.

Noticeably, the main proxemic activity took place overlapping to a large degree. However, the activity did not seem to be focused as observed in other experiments: for example, in experiment 22 or individual segments of experiments 1 and 19. This might be due to the nature of the artefact produced, which had quite an elongated shape (Figure 100).

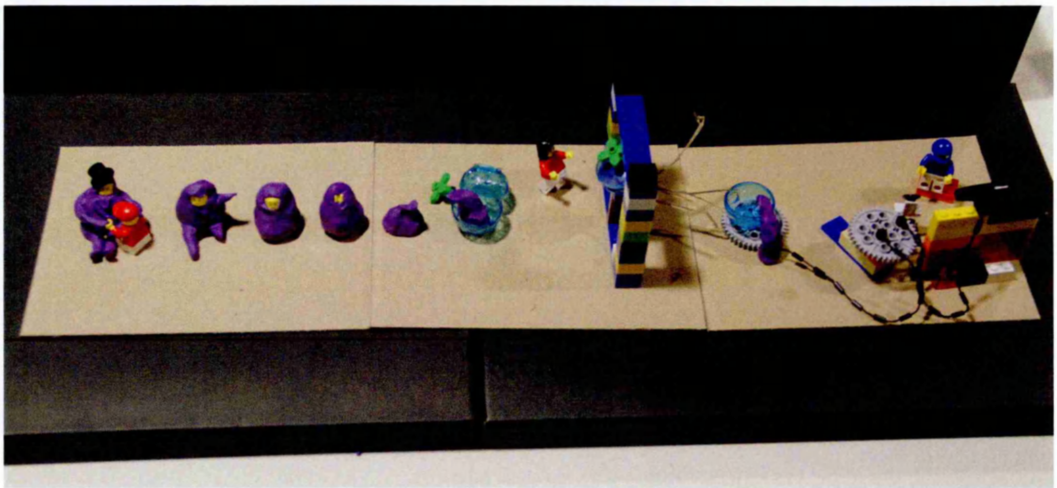


Figure 100: Image of the elongated shape of the artefact produced in experiment 4.

The only significant separation of motion trace activity could be discerned in the segment recording minutes 20 to 25. During this phase of the design process the participants retreated to their personal spaces. This coincided with a period of about two minutes where the participants did not use any prototyping material at all, but where they were reflecting and discussing the next steps in design move 21, "Maybe, we can show the last scene where we're celebrating" and design move 22, "Oh, we can show the part [where] you record the message".

Figure 101 illustrates the types of expressions occurring in the first five minutes of the experiment. Interestingly, in this segment the participants started using clay and Lego before they had agreed upon a design direction. They start with design move 1, proposing "You post a telegram, I open it and a screen appears". After an interjection, asking for incorporating touch into the concept, this original idea is then being developed in a rather linear fashion in the following design moves. Noticeably, the brainstorming phase at the beginning of the design process, observed in other experiments, is very short in this instance, virtually non-existent.

In contrast to most other experiments, the breadth of possible solutions to tackle the design task is not being explored in this initial phase, although, comparatively, the motion traces did occur closer together than observed in other design processes.

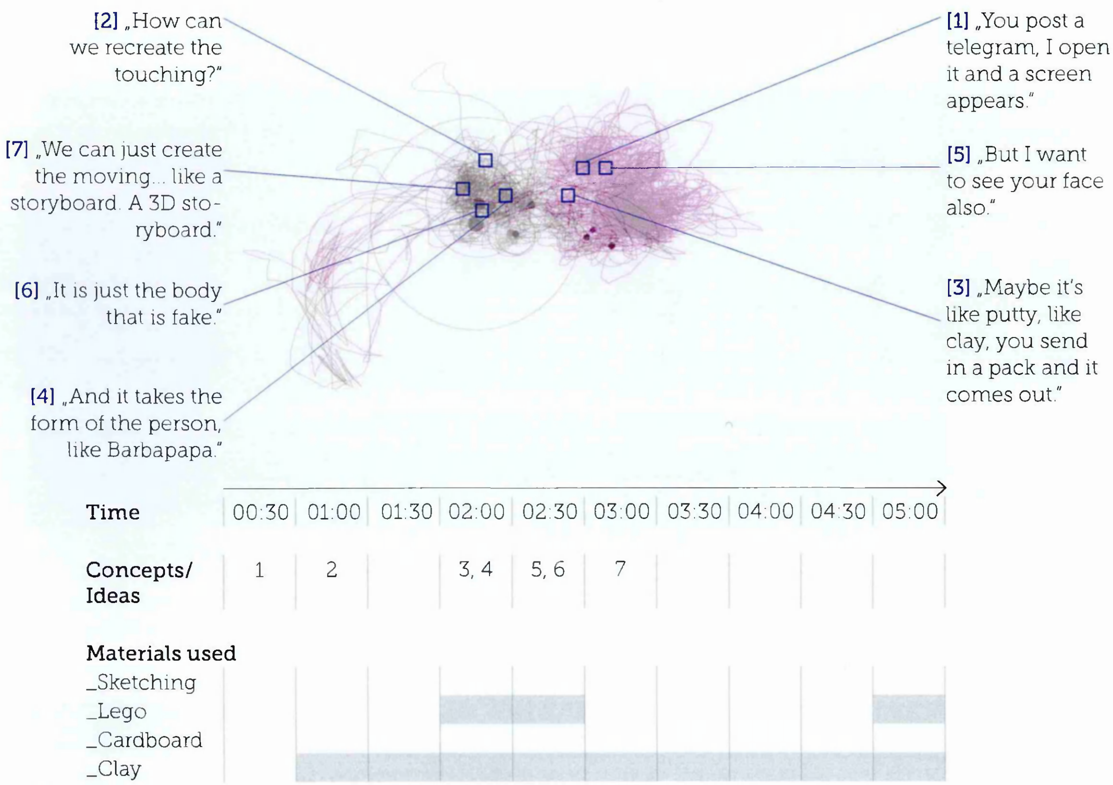


Figure 101: Design moves occurring between minutes 0-5 in experiment 4.

Design move 7 proposes, after about three minutes, how the idea can be manifested in an artefact. While in other experiments, most of the participants remain in the brainstorming phase, this represents a very early notion towards producing a tangible artefact, echoing the rather linear nature of the design activity.

Figure 102 illustrates this observation in more detail. While in the previous segment the design moves represented somewhat general propositions for the design solution, after about five minutes, they express very specific and relatively small iterations or design decisions focused on the production of the artefact. The shapes of the recorded motion traces indicate overlapping but also individual activities not directly taking place in the middle of the interpersonal space, depicting an interplay of individual reflections and joint work on the artefact.

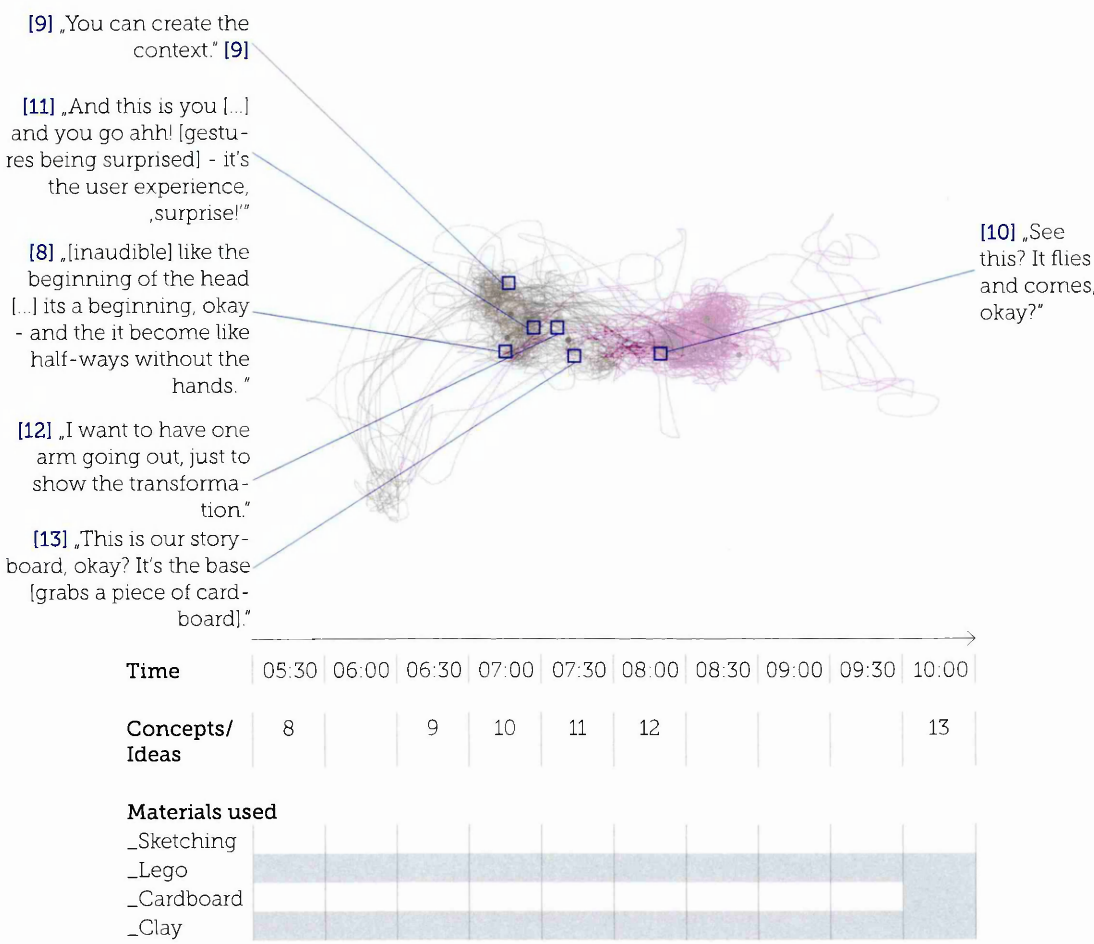
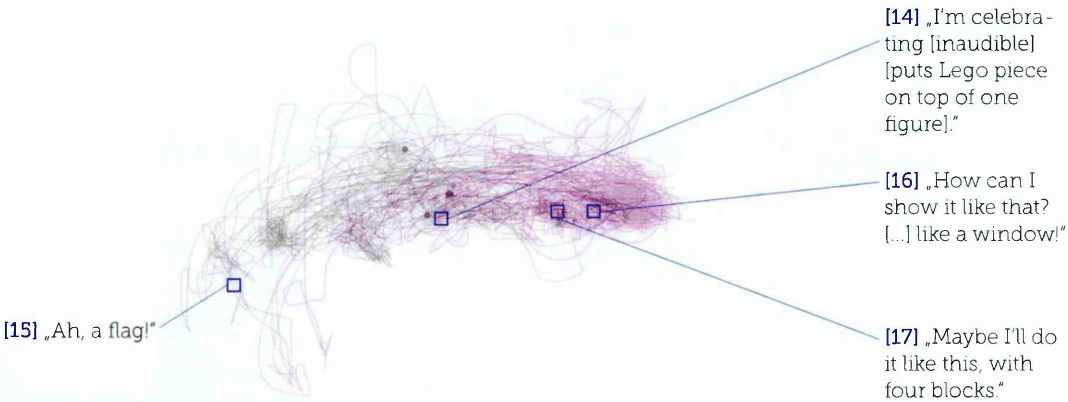


Figure 102: Design moves occurring between minutes 5-10 in experiment 4.

In segment 3 (Figure 103) the participants continue to refine their design solution, seemingly being inspired by the Lego elements.



Time	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
Concepts/ Ideas				14		15		16		17
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 103: Design moves occurring between minutes 10-15 in experiment 4.

Notably, Figure 104 depicts a segment with relatively few proposed design moves, but continuing motional activity. As investigated previously in the measurements of the rate of talk in design processes, in this segment, too, design activities not amenable to verbalisation might predominate. This would be somewhat in accordance with the discerned notion towards the production of an artefact and the early use of the prototyping materials.

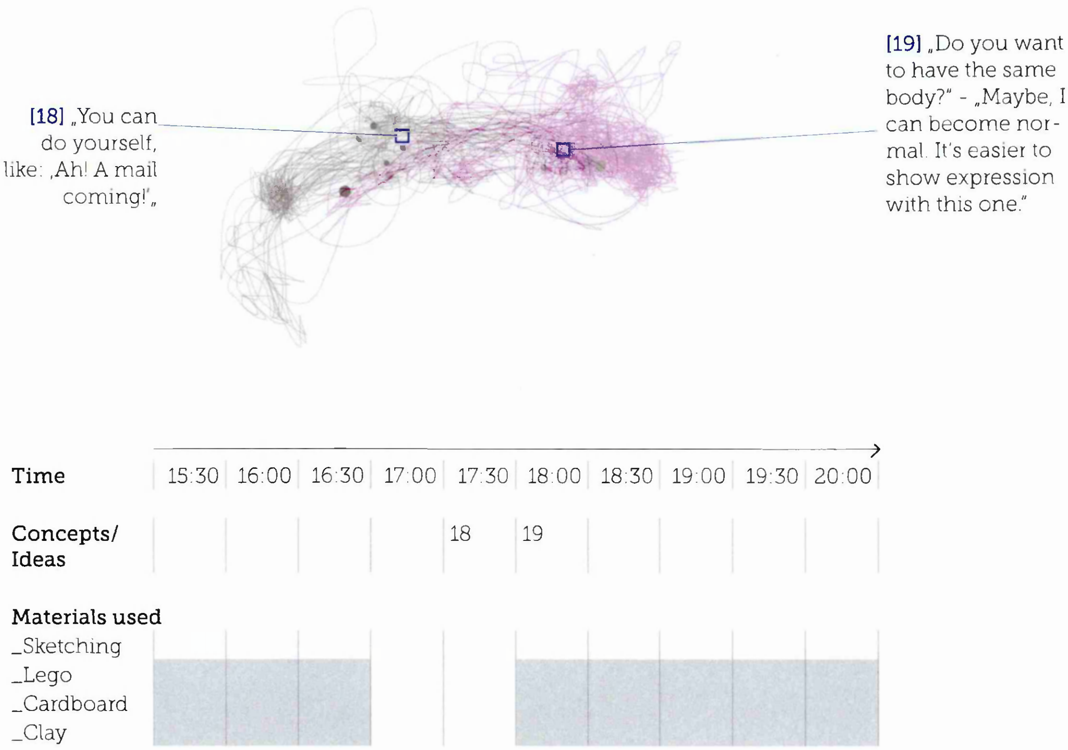


Figure 104: Design moves occurring between minutes 15-20 in experiment 4.

In the segment shown in Figure 105, the motion traces separate themselves from each other distinctively. While in all other segments of this experiment, the traces appear rather closely connected, after about 22 minutes into the design process, the participants take a step back and to reflect for a brief moment, not using any prototyping media between minutes 22 and 24. The thoughts expressed in the individual design moves echo a reorientation of the process taking place. The consecutive design moves 21 ("maybe, we can show the last scene where we're celebrating") and 22 ("oh, we can show the part [where] you record the message") express the participants' search for possibilities or directions in which to develop their design solution. Interestingly, this reorientation did not produce any dots or circles indicating motional inactivity. This was due to the specific use of the artefact, which was not worked on during that phase in a physical sense, but served as an externalised concept in which specific parts were pointed out in the discussion.

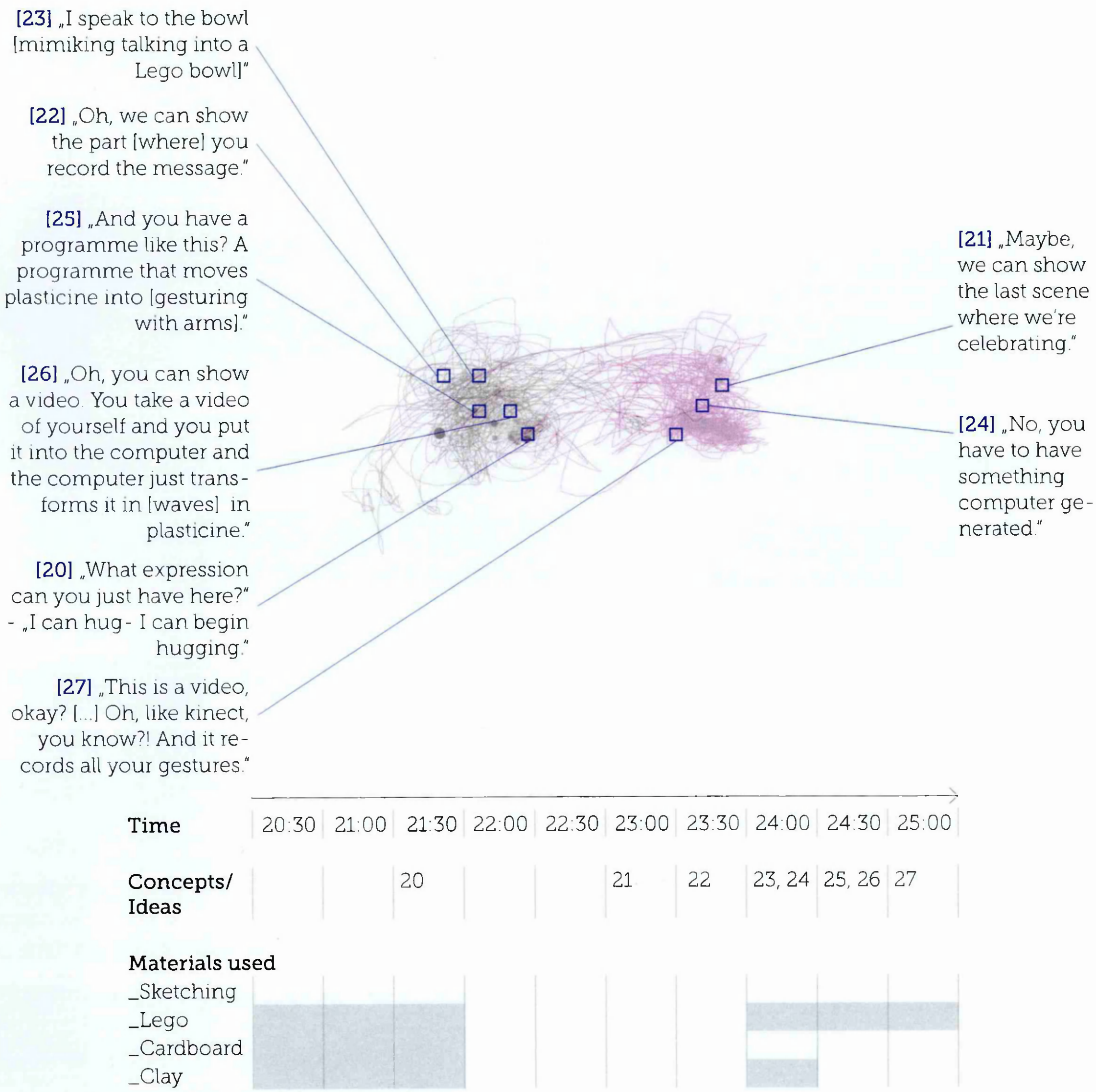
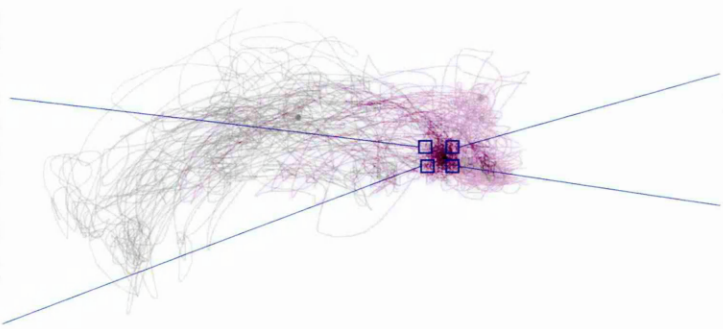


Figure 105: Design moves occurring between minutes 20-25 in experiment 4.

In the last segment (Figure 106) the participants continue working with Lego until minute 28 with a high intensity in the motional activity.



Time	25:30	26:00	26:30	27:00	27:30	28:00	28:30	29:00	29:30	30:00
Concepts/ Ideas		28, 29				30, 31				
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 106: Design moves occurring between minutes 25-30 in experiment 4.

Linkograph

Taking a closer look at the linkograph depiction of the design process in experiment 4, the observations made above can be seen, too. The rather linear thinking early on in the process, is represented by the slightly opened up sawtooth pattern (which is also, to some degree, distorted by the gap between design move 7 and 8, due to the combined depiction with the PMTA). Only four orphan moves can be counted throughout the experiment. Particularly in the early brainstorming phase, where the proposition of design moves which are not developed any further is expected, only two orphan moves can be recorded.

Significantly, in the two segments between minutes 10-15 and minutes 15-20, the observation of non-verbalised design activity made in Figure 104 appears to be echoed. Although only very few verbalised design moves are recorded during this period, the motional activity did not seem to decline. Quite on the contrary, when looking at the PMTAs in these two segments, the patterns visualised seem to show the most connected and overlapping motion traces of the design process, indicating a very active and close collaboration.

In the last two segments, a triangle pattern or chunk emerges. According to Goldschmidt (2014), chunks represent "cross-examination of relevant properties, related questions, and possible implications of a design issue" (p. 63). Such an interpretation of the linkograph in experiment 4 seems to be sensible. From the start of the design process up to two-thirds into the experiment, the two participants were rather focused on generating a physical artefact of the original idea proposed. Between minutes 22 and 24 they paused to reflect on their design solution. While continuing their work, they simultaneously examined and evaluated their design in the last phase of the design process, resulting in the chunk pattern seen between design moves 22 and 29.

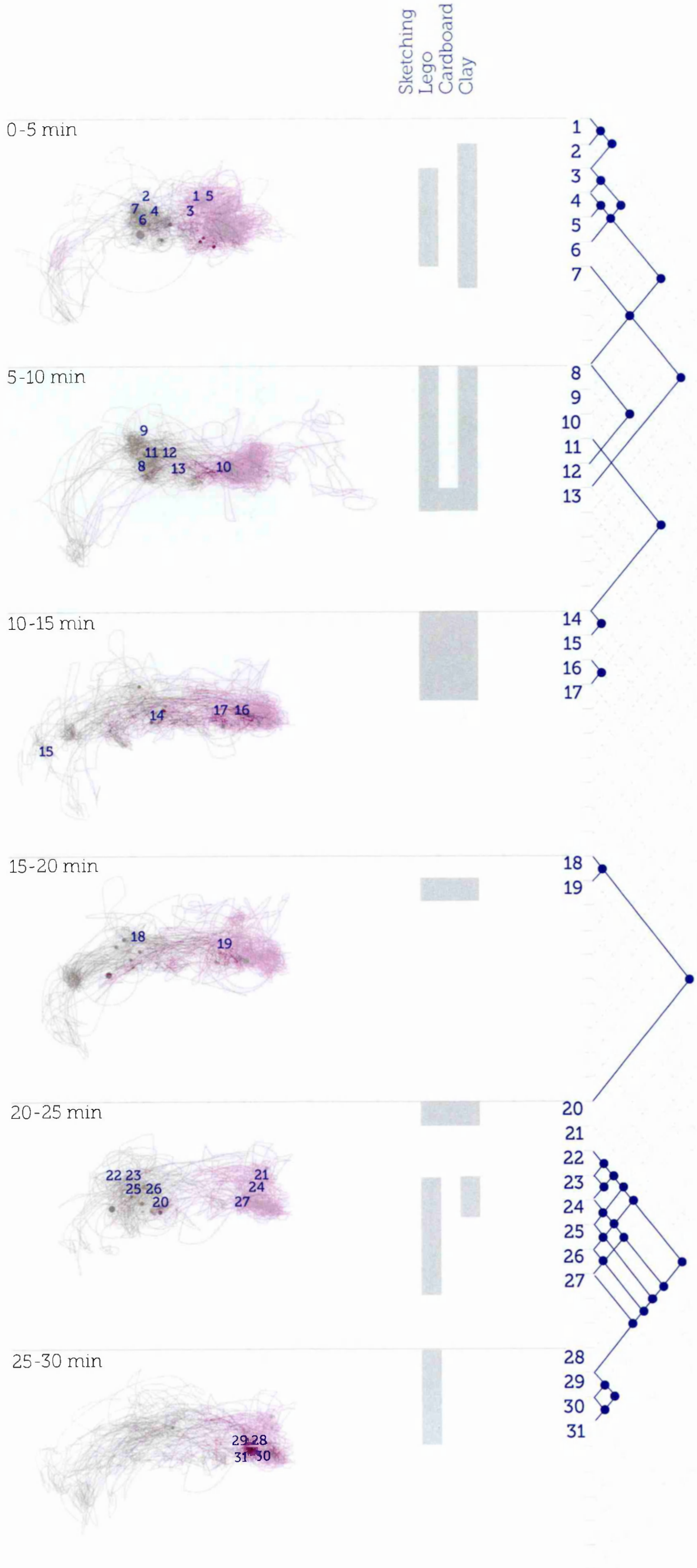


Figure 107: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 4.

Artefacts produced

As the most striking feature of the prototype produced in this experiment, the elaborateness of the artefact catches one's eye (Figure 108). Relying mainly on Lego and clay, as well as on cardboard to support the individual objects, the prototype shows various specific features of the design solution, as well as a transition occurring while the device is in use. This elaborated prototype might be seen as a direct outcome of the highly connected collaboration.

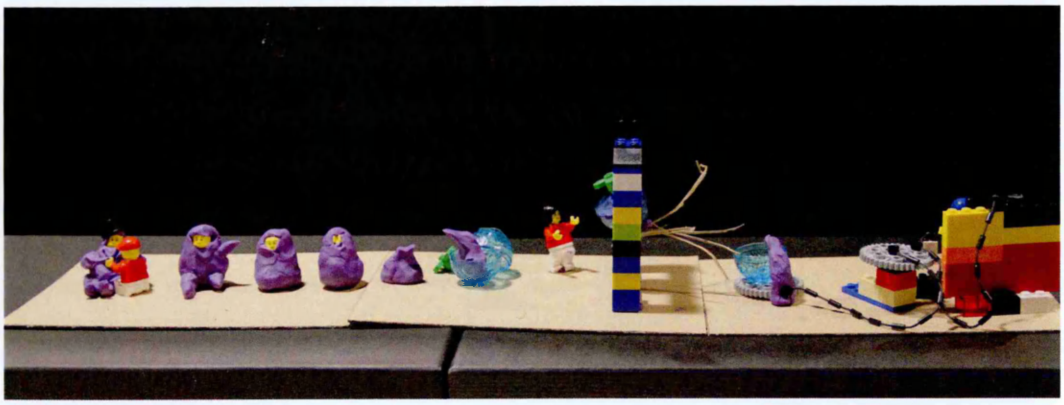


Figure 108: Elaborated prototype build with Lego, clay and cardboard.

Connectedness

Analysing the degree of connectedness, the scores calculated for experiment 4 seem to indicate a very connected collaborative design activity taking place (Figure 109). Throughout the whole process, the highest value of 3 is being recorded regarding the degree of symmetrical motion traces and synchronous motional activity. Notably, the values for the degree of linkage between the design moves are, with one exception, being evaluated at the highest score. The overall scores show four out of six segments with the highest total score of nine.

Experiment 4 | *Connected Individual Collaboration*

Degree of Connectedness per Observational Segment

	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min	30-35 min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	3	3	3	3	3	3	-	-
Ratio of contributed ideas/design moves	3	1	2	3	2	3	-	-
Degree of linkage between ideas/design moves	3	2	3	3	3	3	-	-
Degree of connectedness	**9**	**6**	**8**	**9**	**8**	**9**	**-**	**-**

(Lowest value: 3, highest value: 9)

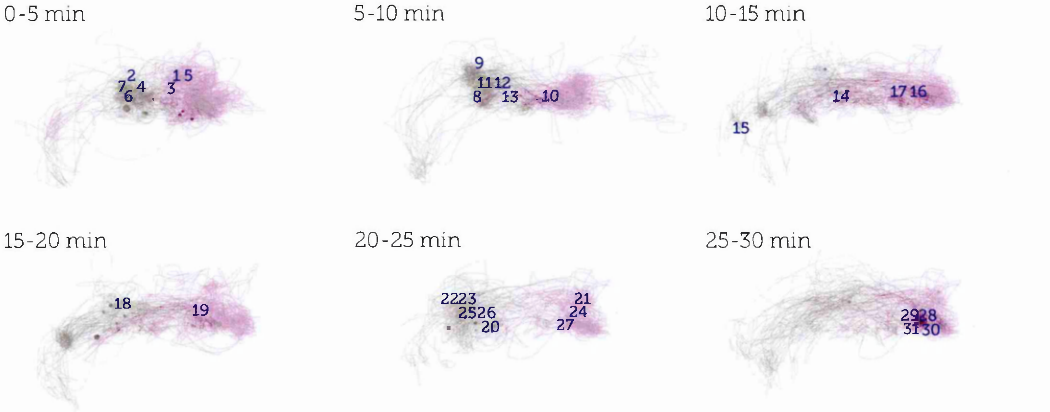


Figure 109: Evaluation matrix for the degree of connectedness and PMTAs of the individual phases of experiment 4.

The PMTA of this experiment illustrates the lack of a brainstorming phase at the beginning of this design process, and that the participants started to work in the interpersonal space with prototyping materials right away. The lack of brainstorming activity is also indicated by the very high degree of linkage between the design moves, due to the fact that no, or almost no orphan moves were proposed in the early stage of the process. With the early stage usually being the phase where ideas are thrown in by the participants in a very tentative manner, this illustrates that the participants started building one specific design solution right away.

Segments 2, 3 and 5 are the only ones not to show the highest value of 9. In segment 2 the motion traces seem to be very symmetrical with the values for the contributed design moves and their linkage slightly weakening. However, with both participants very much engaged in the design process, a slight bias towards one participant at times seems to be natural and not indicating a general or significant change in the nature of the design process overall.

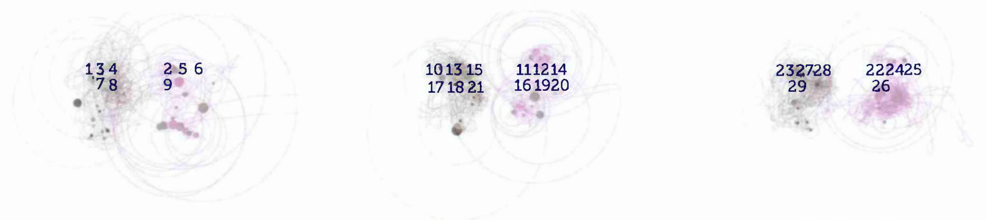
Summary of experiment 4

Experiment 4 is characterised as a connected individual collaboration. Using the same materials as in the previous example, the participants started to prototype right at the beginning of the task. This resulted in phases with very few verbalised design moves but continuous motional activity. The motion traces were overlapping, but less focused in the interpersonal space as in the previous example, resulting in a more individual type of design activity. Notably, the motional activity was paused for phases of mutual reflection of the artefact, illustrating the emergence of the design solution from collaboratively working on the prototype. This observation could also be made in the linkograph of this experiment. The early phase shows a rather linear type of thinking with each design move building upon the other and very few orphan moves. Only at the end could a thorough cross-examination of the design solution be recorded in a triangle shape of design moves, further illustrating the gradual emergence of the final design solution from the collaboration.

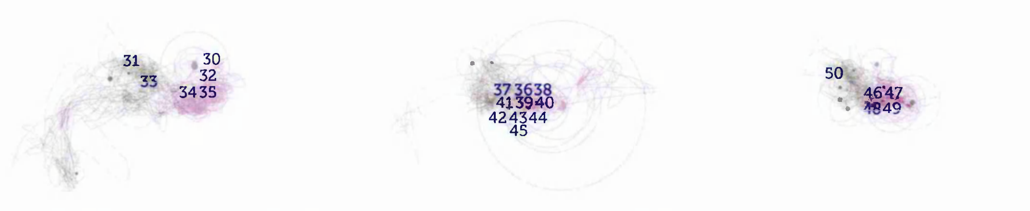
While in the final design solutions of the two experiments documented above all three prototyping media were used to some extend, the next example documents an experiment where the participants focused more on one specific three-dimensional prototyping material in their final solution, following an extensive brainstorming phase.

6.3.3 Experiment 5: a thorough investigation

Experiment 5 is an example of a thorough investigation, featuring a prolonged brainstorming phase with no prototyping activity whatsoever. Clay was only used as prototyping material after 14 minutes into the process (Figure 110). The number of design moves, especially in this early phase, appears to be significant. 28 moves could be recorded before the participants started to use prototyping media. During that phase, the participants largely remained in their personal spaces, not interacting much in the interpersonal space. However, the process was quite symmetric in the sense that both contributed about equal numbers of design moves in this period (15:14 design moves).



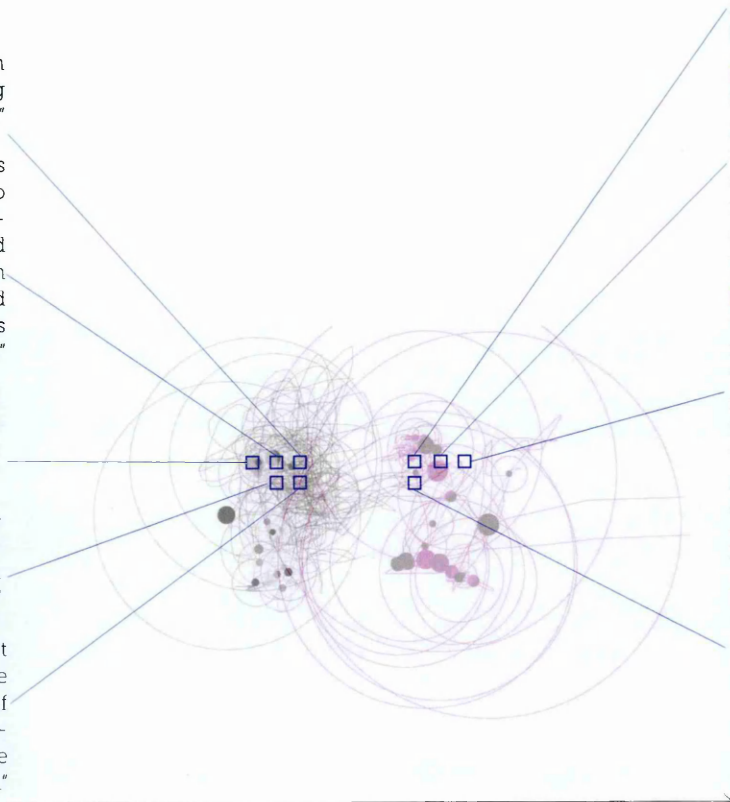
										5 min										10 min										15 min
										Minutes										Minutes										Minutes
		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15
										Concepts										Concepts										Concepts
		1, 2, 3			4	5	6	7	8	9	10	11	12	13, 14	15, 16, 17		18	19, 20	21		22	23	24		25	26	27	28	29	
										Materials used										Materials used										Materials used
Sketching																														
Lego																														
Cardboard																														
Clay																														



										20 min										25 min										30 min
										Minutes										Minutes										Minutes
		16		17		18		19		20		21		22		23		24		25		26		27		28		29		30
										Concepts										Concepts										Concepts
	30	31	32	33	34					35	36	37, 38	39, 40	41	42, 43		44	45				46				47		48, 49	50	
										Materials used										Materials used										Materials used
Sketching																														
Lego																														
Cardboard																														
Clay																														

Figure 110: Emergence of ideas and concepts in experiment 5.

Figure 111 illustrates the lively exchange of ideas between the two participants in the brain storming phase.



Time	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00
Concepts/ Ideas		1, 2, 3			4	5	6	7	8	9
Materials used _Sketching _Lego _Cardboard _Clay										

Figure 111: Design moves occurring between 0-5 minutes in experiment 5.

Figures 112 and 113 illustrate the tentative nature of the design moves recorded in the brainstorming phase.

[15] „Then you would need some kind of jewellery. But what about guys?"

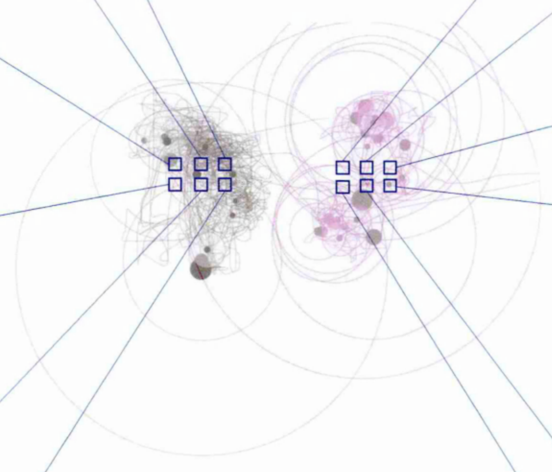
[13] „Or maybe there's like [inaudible] a present, for example ear rings, and then whenever they think of you something happens with them, you feel it that they think of you?"

[10] „Maybe we can work more with what we smell and taste? [...] For example if someone's sad and you would usually send them chocolate you could send them something that smells, tastes like chocolate. "

[17] „Maybe warm or cool, temperature as well? It could combine things. You know like these rings that change colour depending on which temperature it is?"

[18] „But you can't just have ten rings because you have ten friends [...] Maybe like a bracelet and you have the chain, the parts of it [...] and it's symbolic in a way"

[21] „Maybe it's like dropbox, and it's connected with the same [...] bead, and it's the same [...] whatever you do with it the other person sees is."



[11] „Just like in the old movies when people send a love letter with all this perfume on it."

[12] „Or different structures which have a recognisable material?"

[14] „Maybe with different colours, that you send like different moods."

[20] „Or like these things you had in the beginning of all this computer stuff. A little computer chain with an animal in it that you have to take care of it [...]" - „Oh, tamagochi!"

[19] „Like a cross or a heart. Or it smiles."

[16] „A key chain? On your bag or-"

Time	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00
Concepts/ Ideas	10	11	12	13, 14	15, 16, 17		18	19, 20	21	

Materials used
_Sketching
_Lego
_Cardboard
_Clay

Figure 112: Design moves occurring between 5-10 minutes in experiment 5.

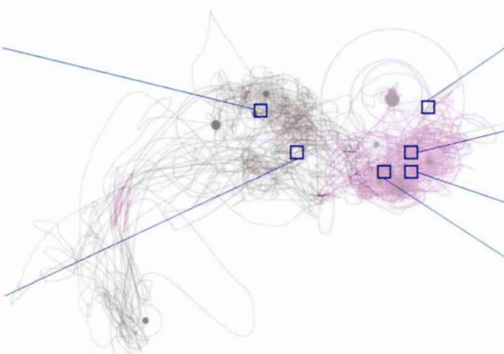
Characteristically, the proxemic motion trace patterns remained separated in this brainstorming phase while they converged as soon as three-dimensional prototyping media were used in the second part of the design process.

Time	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
Concepts/ Ideas	22	23	24		25	26	27	28	29	
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 113: Design moves occurring between 10-15 minutes in experiment 5.

The nature of expressions in the two segments depicted in Figures 112 and 113 shows a certain degree of open exploration. While some design moves remain not elaborated and are being quickly abandoned (like design moves 16 or 21), others are being explored in more detail or picked up later (like design moves 14 or 17). It seems that the participants are in this phase exploring different design directions without committing to any one in particular, looking for a central idea and concepts to integrate.

After about 14 minutes into the design process, three-dimensional prototyping media are being used and the motional traces begin to converge in the interpersonal space soon after this (Figures 114).



Time	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00
Concepts/ Ideas	30	31	32	33	34					35

Materials used
_Sketching
_Lego
_Cardboard
_Clay

Figure 114: Design moves occurring between 15-20 minutes in experiment 5.

As previously observed, when starting to use prototyping media, the nature of design moves changed. In design move 38, for example, one participant was inspired by a feature of the prototype when proposing "oh, maybe this one lights up when there's a new thing." Design moves 39 and 42 are much the same in seemingly being inspired by physical features of the artefact (Figure 115).

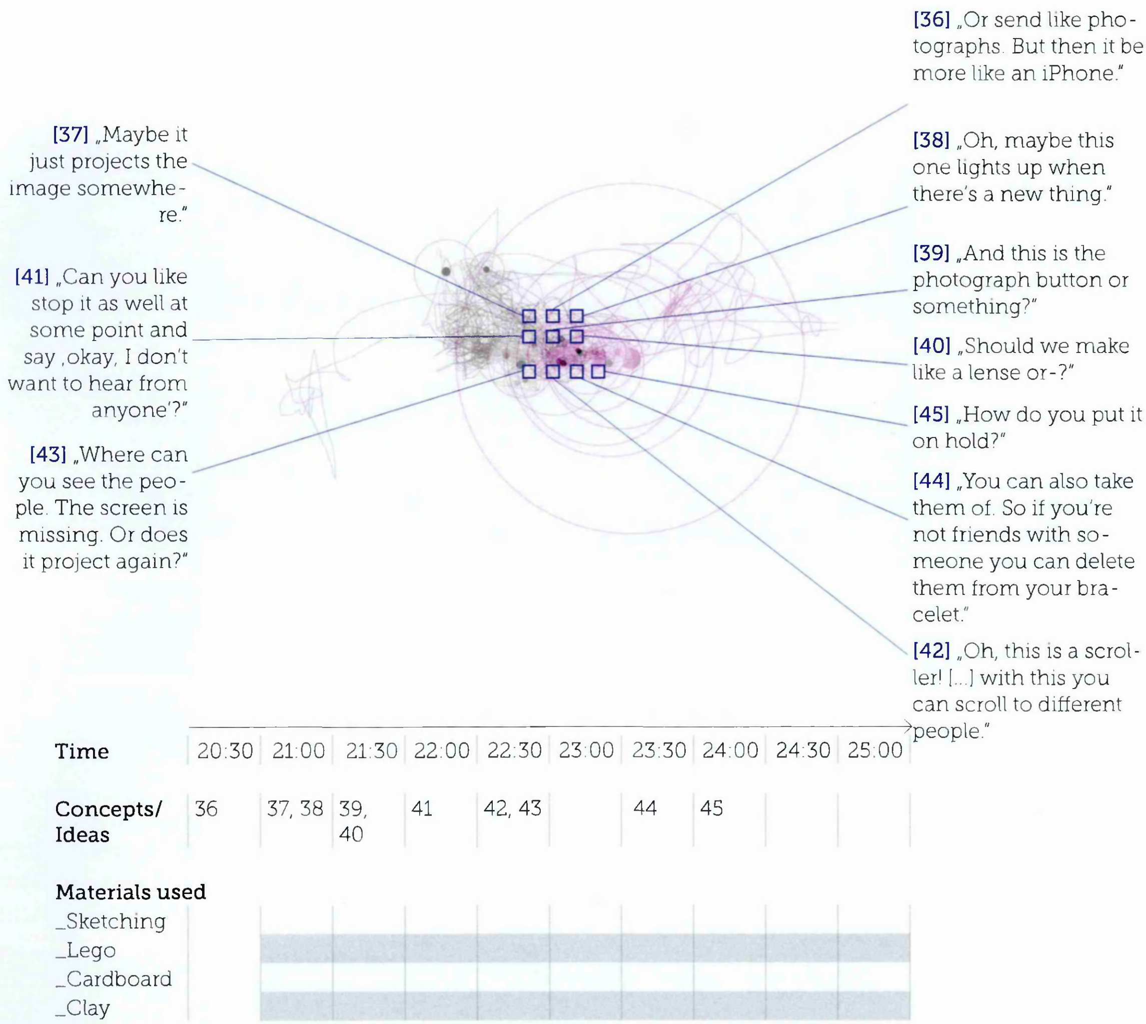


Figure 115: Design moves occurring between minutes 20-25 in experiment 5.

However, the other design moves also seem to slightly change in nature. While in the discussions in the former segments, the ideas were more concerned with a general design direction, they are more specific once prototyping media are being used. In design move 25, when the participants were still brainstorming without using any prototyping materials, a proposition for a general design direction is being proposed ("We could do the temperature thing. If you would have a bracelet, the thing under it would heat up"). A different kind of design move was, for example, number 43, where Lego and clay are being used to prototype, asking: "Where can you see the people? The screen is missing. Or does it project again?" The discussion here had moved quite a little more into the depth of the different aspects of the design solution. This observation can also be made in Figure 113. Notably, when looking at the segments where the three-dimensional prototyping media are being used, most ideas seem to originate from an activity in the interpersonal space between the participants (Figure 116).

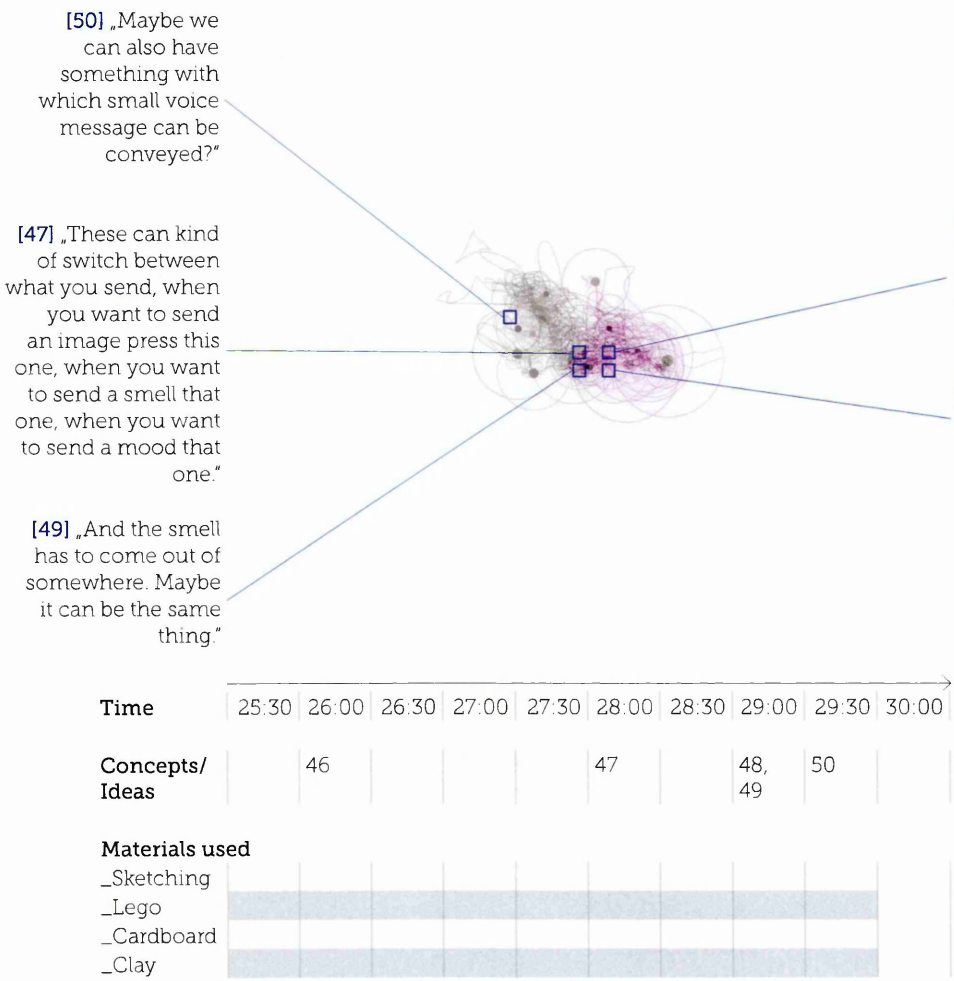


Figure 116: Design moves occurring in minutes 25-30 of experiment 5.

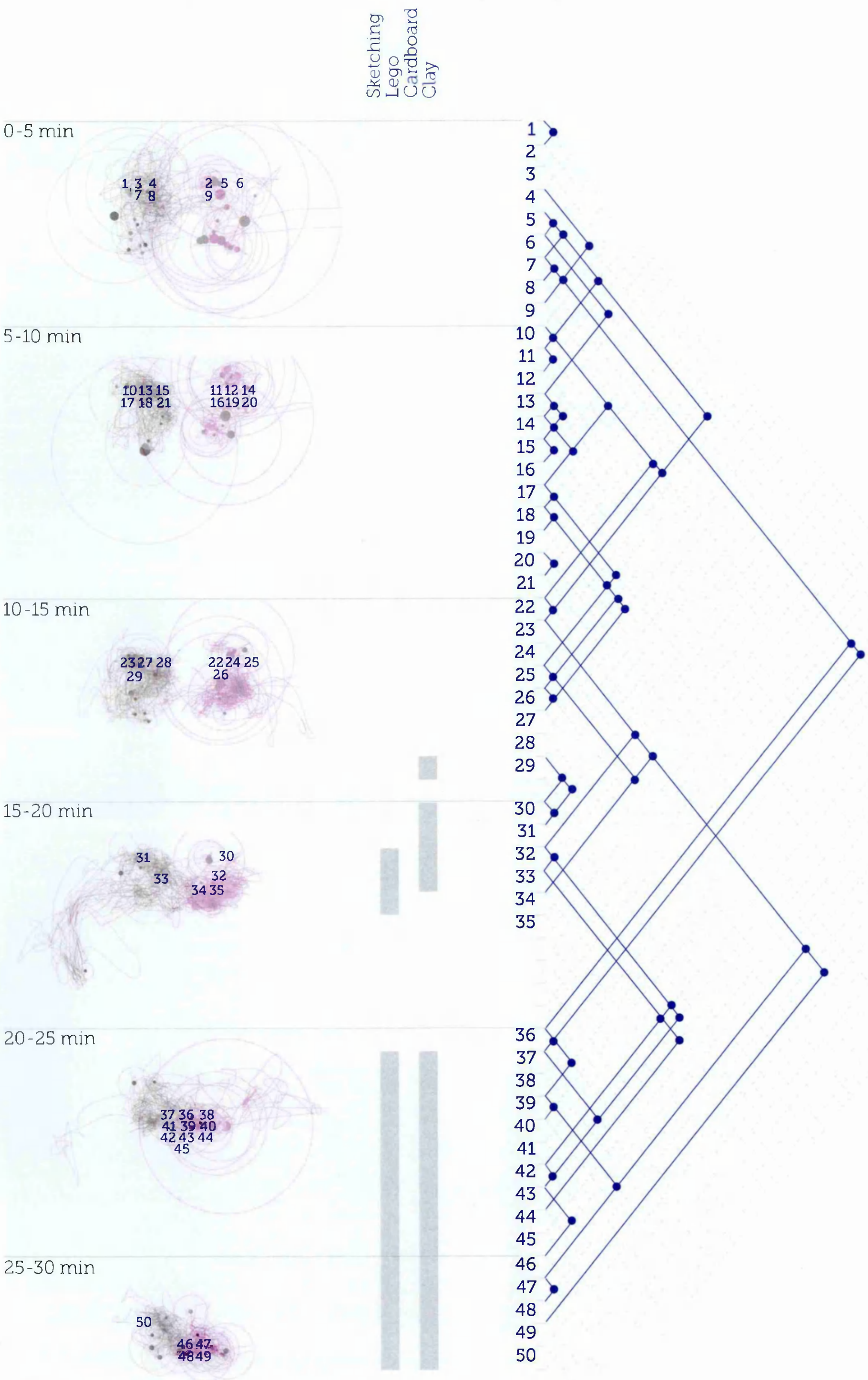


Figure 117: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 5.

Linkograph

The linkograph of experiment 5 reveals the highly connected character of the design process. A few orphan moves are dispersed over the design process, as well as a few instances of short phases of linear thinking, indicated by short sawtooth patterns (e.g. between design moves 13, 14, 15, 16 or 29, 30, 31). However, the predominant pattern is in the form of a web. This pattern characterises the design process as thoroughly investigating and connecting different design solutions and issues throughout the experiment. The relatively large amount of design moves remains unaccounted for, with the data not revealing whether this was, for example, due to personal traits of the participants which were not assessed in this experimental set-up.

Design move 7, proposing "pictures that communicate with you that move" and design move 23, suggesting "It could be a lot of things. It could either be the smell or maybe moods as well", possess the longest link spans. Both seem to be integrated in the final design solution (Figure 118), with three screens in the middle of a bracelet and integrated vaporising fuses.

Artefacts produced

The prototype built as final design solution represents quite an elaborate device. While relying mostly on clay to form the artefact, many features are imprinted onto the material. The way this was done indicates that not only functional aspects have been taken into consideration while producing the prototype, but also aesthetic properties. The density of features and the concise shape indicates that the participants had a profoundly shared understanding of the design direction.

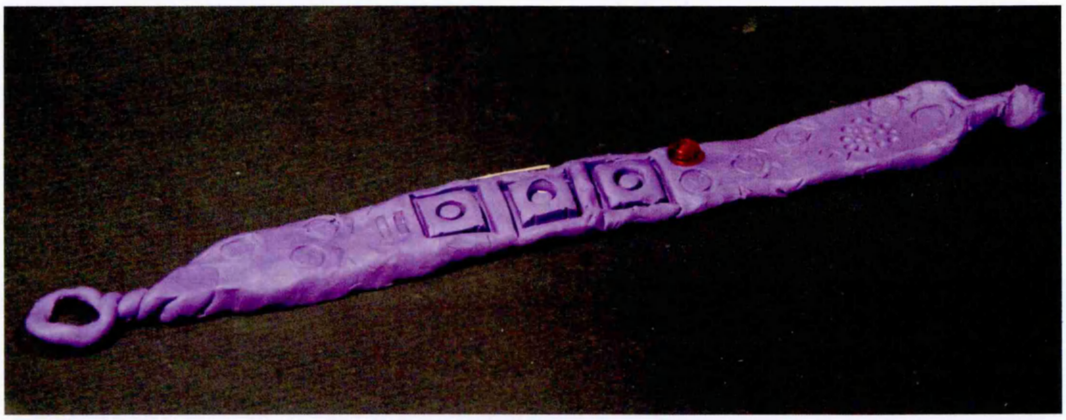


Figure 118: Artefact generated in experiment 5 as final design solution.

Connectedness

Measuring the degree of connectedness, experiment 5 shows rather high values overall, although most of them do not peak at the highest value of 9 (Figure 119). In the beginning, there appears to be a slight imbalance regarding the symmetry of the motion traces. However, the PMTAs for the first three segments show the separated pattern typical for the early brainstorming phase, with the majority of the motional activity taking place in the personal spaces of the participants. Notably, the PMTAs indicate the brainstorming phase lasting until the middle of the whole design process. With the values for the degree of linkage between the individual design moves, this combination suggests that a very active verbal exchange of ideas back and forth between the participants took place during that phase. While the values to not change much in the later segments, the PMTAs show the motional activity converging in the interpersonal space between the two participants. Furthermore, while design moves are continually being contributed to the design process, the place where they seem to be inspired or originate from tends towards the interpersonal space. This might indicate that an idea for the design solution was found and agreed upon in the brainstorming phase, but kept on developing while the participants were devising a prototype.

While overall the collaborative design activity observed in this experiment shows a high degree of connectedness, at times, slight changes in the nature of the collaboration seemed to take place. In segment 3, for example, the linkage of design moves weakened. In other instances, like segment 4, the ratio of contributions dropped slightly.

Experiment 5: Degree of Connectedness per Observational Segment

	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min	30-35 min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	2	2	3	3	3	3	-	-
Ratio of contributed ideas/design moves	3	3	3	2	1	2	-	-
Degree of linkage between ideas/design moves	3	3	2	3	2	3	-	-
Degree of connectedness	**8**	**8**	**8**	**8**	**6**	**8**	**-**	**-**

(Lowest value: 3, highest value: 9)

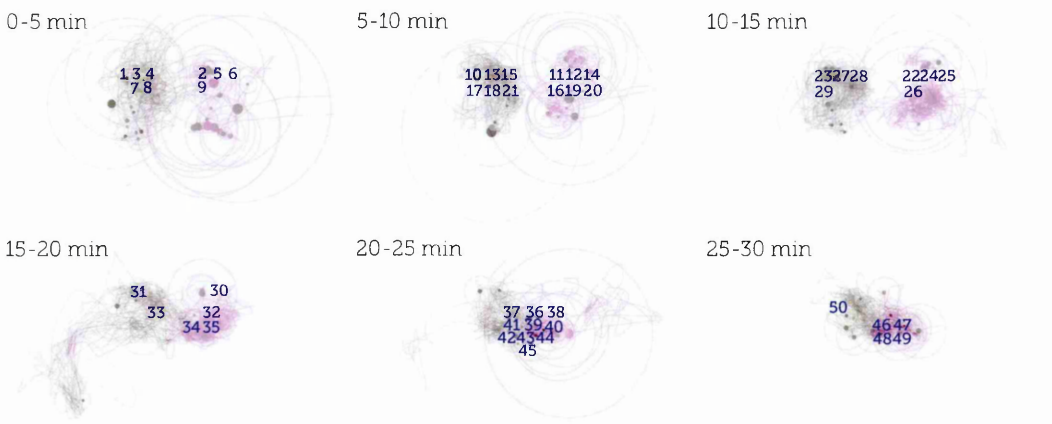


Figure 119: Evaluation matrix for the degree of connectedness and PMTAs of the individual phases of experiment 5.

Summary of experiment 5

Characterised as a thorough investigation, the design activity occurring in experiment 5 shows the extensive use of brainstorming in the first part of the experiment and focused prototyping in the second part. The participants only started to use three-dimensional prototyping media in the middle of the design process, after around 14 minutes. 28 design moves were contributed during the first half of the experiment, in about equal measures by both participants, reflecting the joint exploration of various possible design directions. No commitment to any one specific idea could be discerned during brainstorming. As in the previous experiments, once three-dimensional prototyping media were used, the motional activity, which resided up to this point very much within the personal spaces of each participant, converged in the shared space between them. Once prototyping started, the verbal expressions show that the participants were inspired by individual features of the artefact produced. The design moves themselves became more specific when the participants started prototyping, addressing functional or aesthetic aspects of the design solution. Inspired by the brainstorming phase, the design solution emerged from the prototyping activity. Towards the end, the participants focused on the use of one prototyping medium, clay. This produced a rather elaborately designed artefact featuring a high density of functional and aesthetic aspects. The linkograph analysis showed a web pattern – which is typical of a thorough investigation – extending over the whole duration of the experiment. Measuring the connectedness of the collaborative design activity, the scores remained high throughout the experiment, peaking in the highest score in the last segment of the observation.

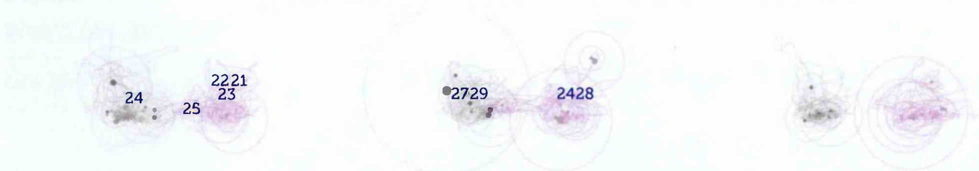
The three experiments analysed above, all using three-dimensional prototyping media, show similar results. The next example will analyse the exclusive use of sketching as the control condition.

6.3.4 Experiment 12: a case of increasing separateness

Experiment 12 illustrates a case of increasing separateness, with the participants only using sketching as the prototyping medium. As a predominant feature of the design activity, the proxemic motion trace patterns of this design process reveal a separated locus of the motional activity for each participant (Figure 120). This separation remained, in various degrees, constant over the whole duration of the experiment. The locus, where the different design moves originated, stayed mostly within the same area. However, for the participant on the right side, five design moves seemed to originate from within the interpersonal space in the middle. This was not the case for the participant on the left side.

As with experiments 1 and 4, in which segments occurred where only very few design moves were proposed, there was a segment in experiment 12 where no design move was verbalised. Quite in contrast to the experiments using three-dimensional prototyping media, in this instance significantly more pauses and periods of inactivity, indicated by dots and circles, can be recorded.

									5 min										10 min										15 min	
									Minutes										Minutes										Minutes	
	1		2		3		4		5		6		7		8		9		10		11		12		13		14		15	
									Concepts										Concepts										Concepts	
1, 2		3	4				5	6	7					8	9, 10, 11		12		13		14	15, 16		17	18	19	20			
									Materials used										Materials used										Materials used	
																														Sketching
																														Lego
																														Cardboard
																														Clay

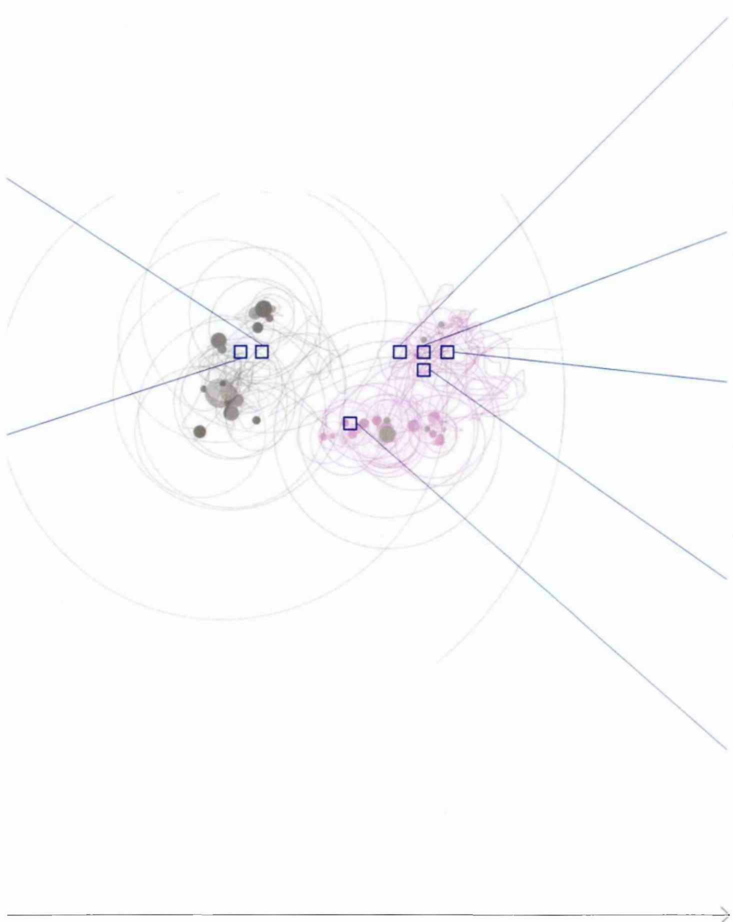


									20 min										25 min										30 min	
									Minutes										Minutes										Minutes	
	16		17		18		19		20		21		22		23		24		25		26		27		28		29		30	
									Concepts										Concepts										Concepts	
	21		22, 23	24			25									26	27, 28, 29													
									Materials used										Materials used										Materials used	
																														Sketching
																														Lego
																														Cardboard
																														Clay

									35 min										40 min										45 min	
									Minutes										Minutes										Minutes	
	31		32		33		34		35		36		37		38		39		40		41		42		43		44		45	
									Concepts										Concepts										Concepts	
		30								31		32																		
									Materials used										Materials used										Materials used	
																														Sketching
																														Lego
																														Cardboard
																														Clay

Figure 120: Emergence of ideas and concepts in experiment 12.

Not surprisingly, the first segment of experiment 12 shows the same brainstorming activity as most of the experiments analysed in more depth in this chapter. The design moves proposed are tentative in nature and explore in a general sense possible design directions (Figure 121). As a focus concept, the transmission of touch emerges in this segment (i.e.. in design move 6).



Time	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00
Concepts/ Ideas	1, 2		3	4				5	6	7
Materials used _Sketching _Lego _Cardboard _Clay										

Figure 121: Design moves occurring between minutes 0-5 in experiment 12.

Once the participants have established a general design direction, they seemed to move forward by refining and elaborating the central aspect. Still in the brainstorming phase, they explore different possible devices that could transmit the sense of touch, as in design move 9, a wearable device, or design move 11, a helmet or a muffler (Figure 122).

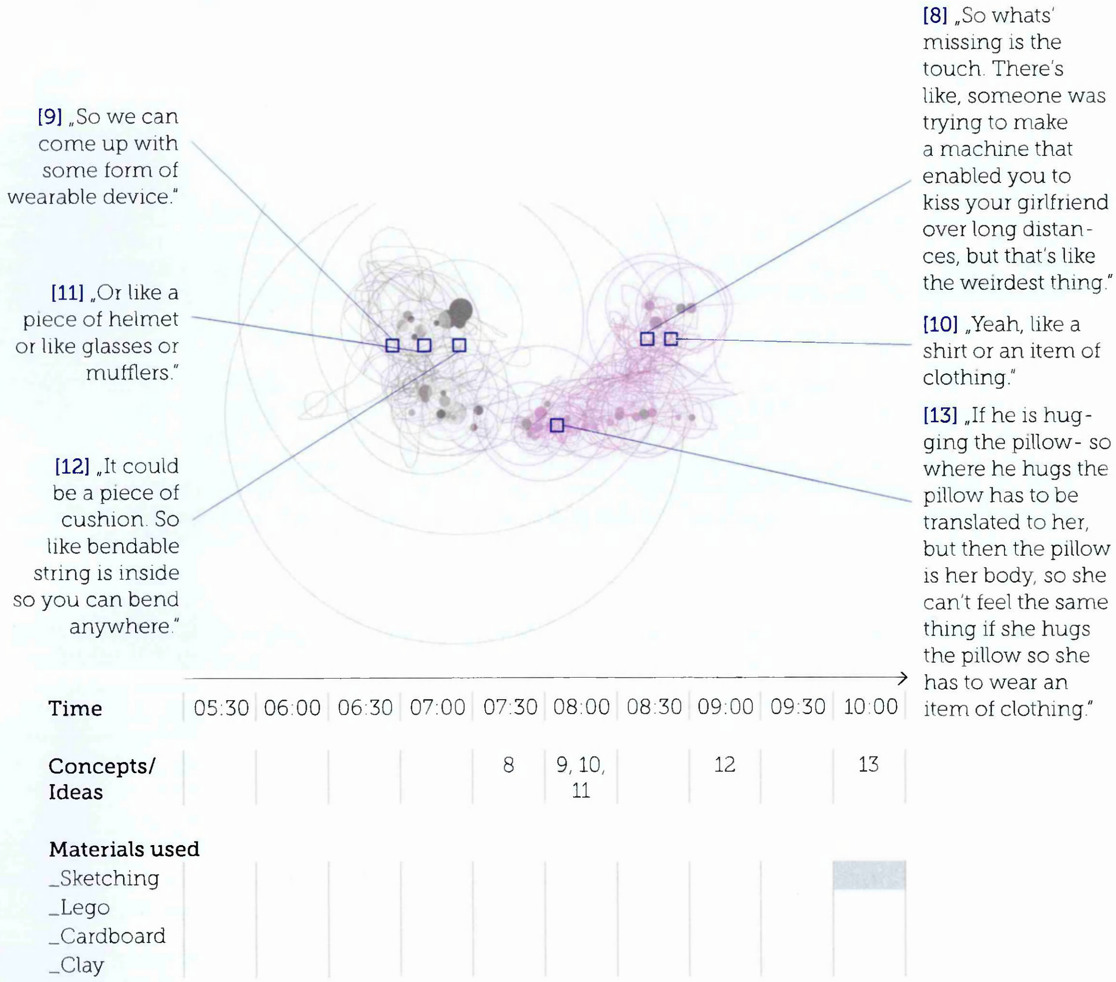
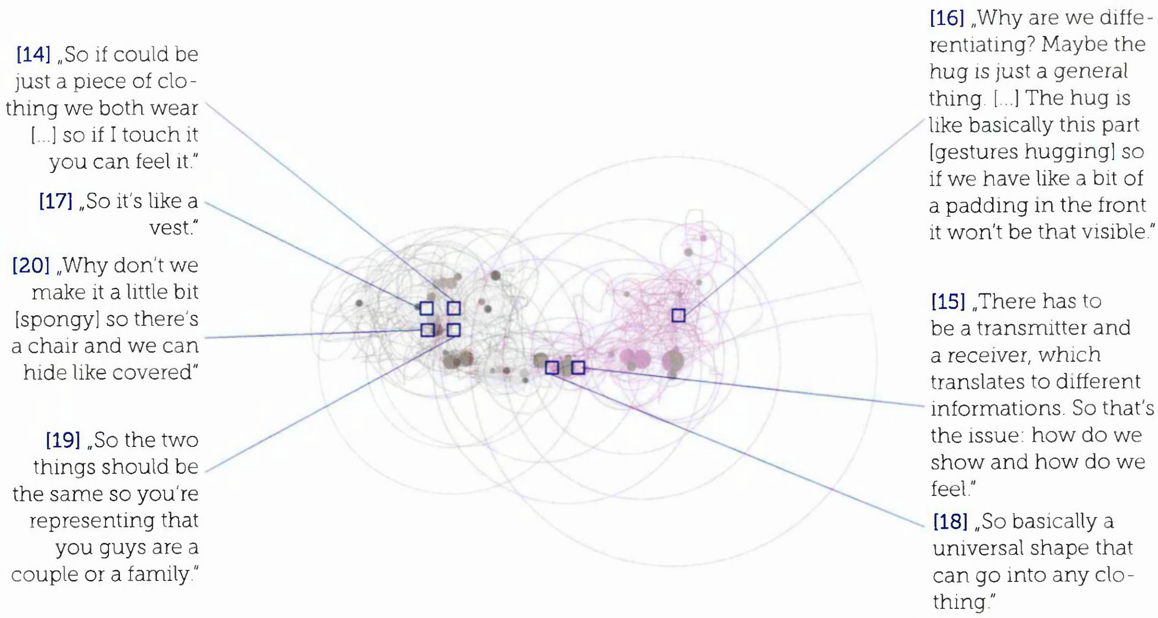


Figure 122: Design moves occurring between minutes 5-10 in experiment 12.

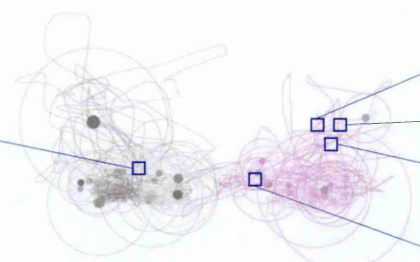
The participants seem to move on to sketching only after they have agreed upon a specific design idea. As illustrated in Figure 123, right before starting sketching in the segment between 10 to 15 minutes, one participant proposes "a piece of clothing we both wear [...] so if I touch it, you can feel it" (design move 14). This observation lends itself to the interpretation that when sketching, often pre-formulated ideas are being externalised, rather than emerging from the activity itself.



Time	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
Concepts/ Ideas		14	15, 16		17	18	19	20		
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 123: Design moves occurring between 10-15 minutes in experiment 12.

In segment 4 (Figure 124) sketching is used almost throughout, with the main part of the contributions contributed by one participant.

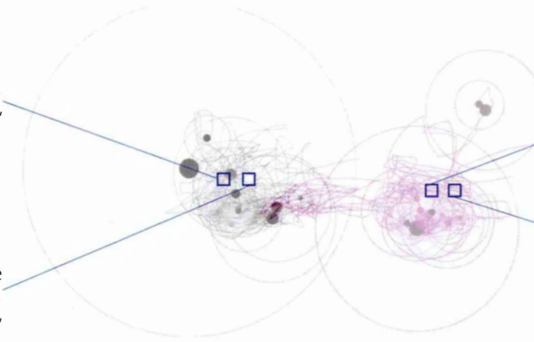


Time	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00
Concepts/ Ideas		21		22, 23	24			25		

Materials used
_Sketching
_Lego
_Cardboard
_Clay

Figure 124: Design moves occurring between 15-20 minutes in experiment 12.

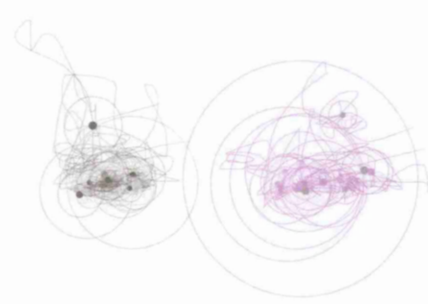
Once the participants have started to sketch, the design moves tend to become more specific, as observed in the other experiments. In Figure 125, between 20 and 25 minutes into the design process, the design moves do represent the depth of the investigation of the design solution. Questions like "how do we relay pressure?" (design move 26) or suggestions like "it could be with a little bit of air" (design move 29) drive the design process forward and explore functional aspects of the solution.



Time	20:30	21:00	21:30	22:00	22:30	23:00	23:30	24:00	24:30	25:00
Concepts/ Ideas							26	27, 28, 29		
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 125: Design moves occurring between minutes 20-25 in experiment 12.

In figures 126 and 127, the motion traces are distinctively separated while both participants seem to sketch on their own.



Time	25:30	26:00	26:30	27:00	27:30	28:00	28:30	29:00	29:30	30:00
Concepts/ Ideas										
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 126: Design moves occurring between minutes 25-30 in experiment 12.

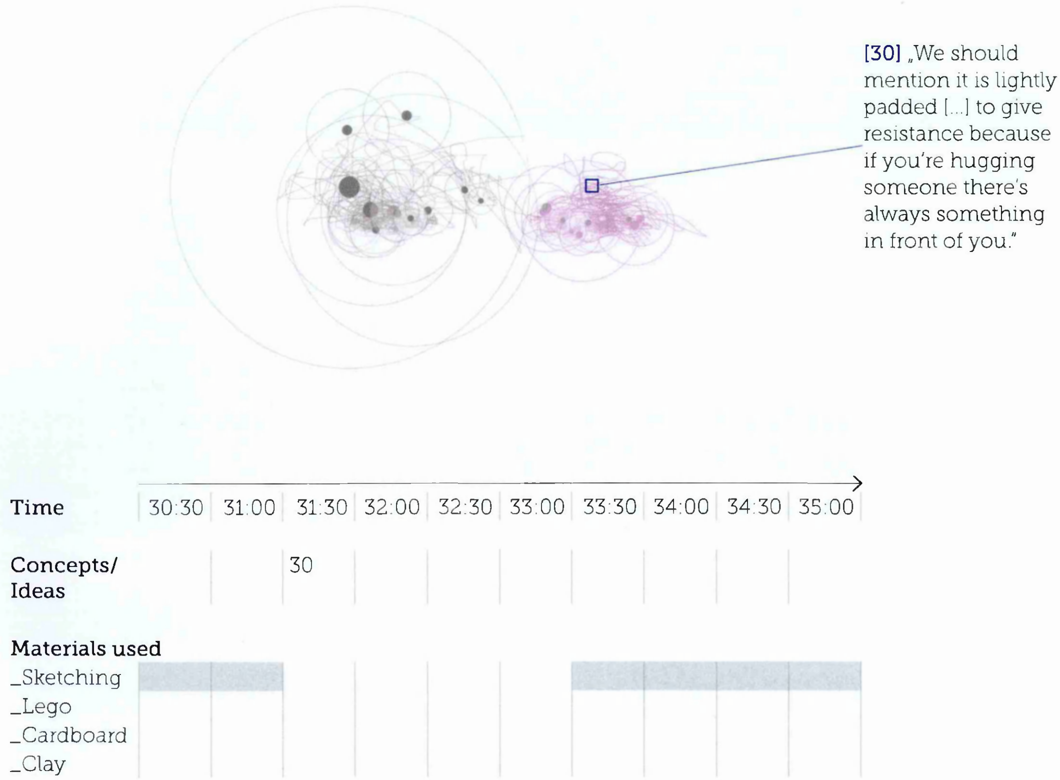
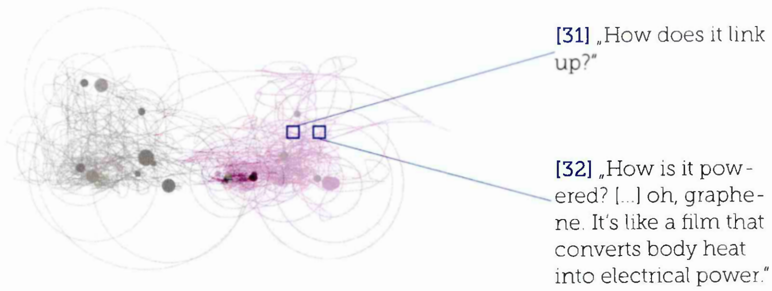


Figure 127: Design moves occurring between minutes 30-35 in experiment 12.

When the participants are engaged in the sketching activity, they seem to be so in a rather individualistic manner. Figure 128 shows both participants being active in their personal space, presumably sketching. The participant on the right seems to reflect and comment on his own sketch. However, there is no interaction with the other participant. The question raised in design move 31, "how does it link up?" goes unresponded, as does the next design move by the same participant, asking "how is it powered?" The question is being answered by the same participant by stating "oh, graphene. It's like a film that converts body heat into electrical power." In this segment, therefore, the discussion was replaced by a monologue.



Time	35:30	36:00	36:30	37:00	37:30	38:00	38:30	39:00	39:30	40:00
Concepts/ Ideas	31		32							
Materials used										
_Sketching										
_Lego										
_Cardboard										
_Clay										

Figure 128: Design moves occurring between minutes 35-40 in experiment 12.

Linkograph

Analysing the linkograph of experiment 12 illustrates a few observations made earlier (Figure 129). Notably, the interaction between the participants by sharing their contribution in individual design moves seems to decrease dramatically as they progress in the design process. The last interaction and mutual contribution of design moves can be recorded between 20 and 25 minutes into the experiment. This leaves about 15 minutes in which no verbalised interaction takes place. Interestingly, one participant contributes three design moves towards the end of the experiment, which are left unresponded to by the other participant. This observation lends itself to the interpretation either that the task of generating a design solution has been split between the two participants, or that collaboration did cease. The former is supported by the fact that the final design solution was presented in a series of drawings that seemed to be assigned to each participant (Figure 130).

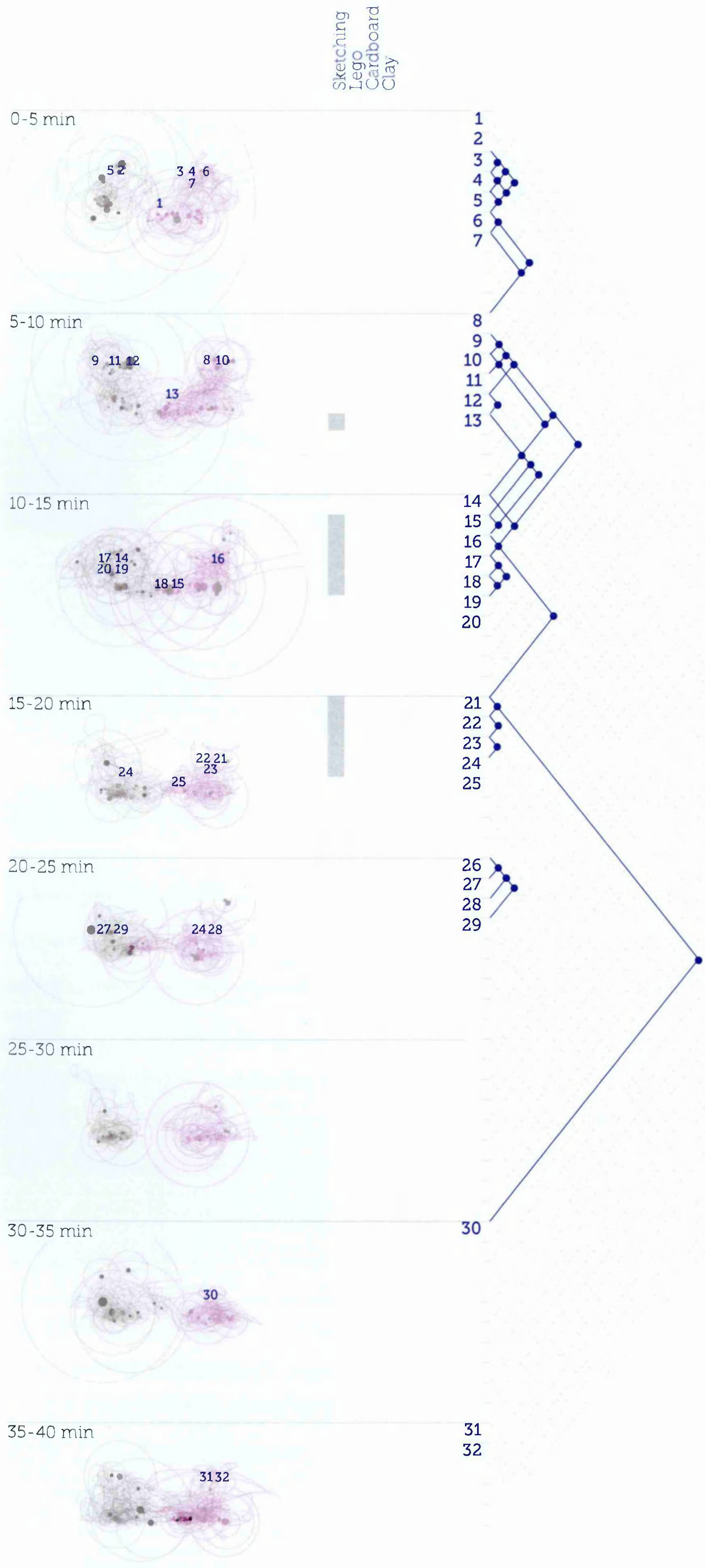


Figure 129: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 12.

Interestingly, however, the participants seemed to explore the design solution early on in the design process. One indication for this is the chunk pattern in between the design moves 9 to 17. In addition, a few instances of sawtooth patterns can be recognised, for example between design moves 21 to 24, indicating brief moments of linear thinking. Another notable observation in the combined PMTA and linkograph depiction of experiment 12 is that the majority of design moves took place when no sketching activity could be observed. 23 moves occurred while no activity was recorded, and 9 moves were proposed while the participants were sketching. This observation raises the question as to whether sketching might lead to an asymmetry in the designing activity and the interaction taking place.

Artefacts produced

The sketches produced in this experiment seem to illustrate the increasing degree of separateness observed earlier. While all three sketches portray a vest that a person would put on to convey messages of loving and care, they differ in the way they would do so. While, in other experiments, rather concise artefacts have been produced (e.g. example F), these sketches indicate a more diverging understanding of the design direction and eventually the design solutions developed.

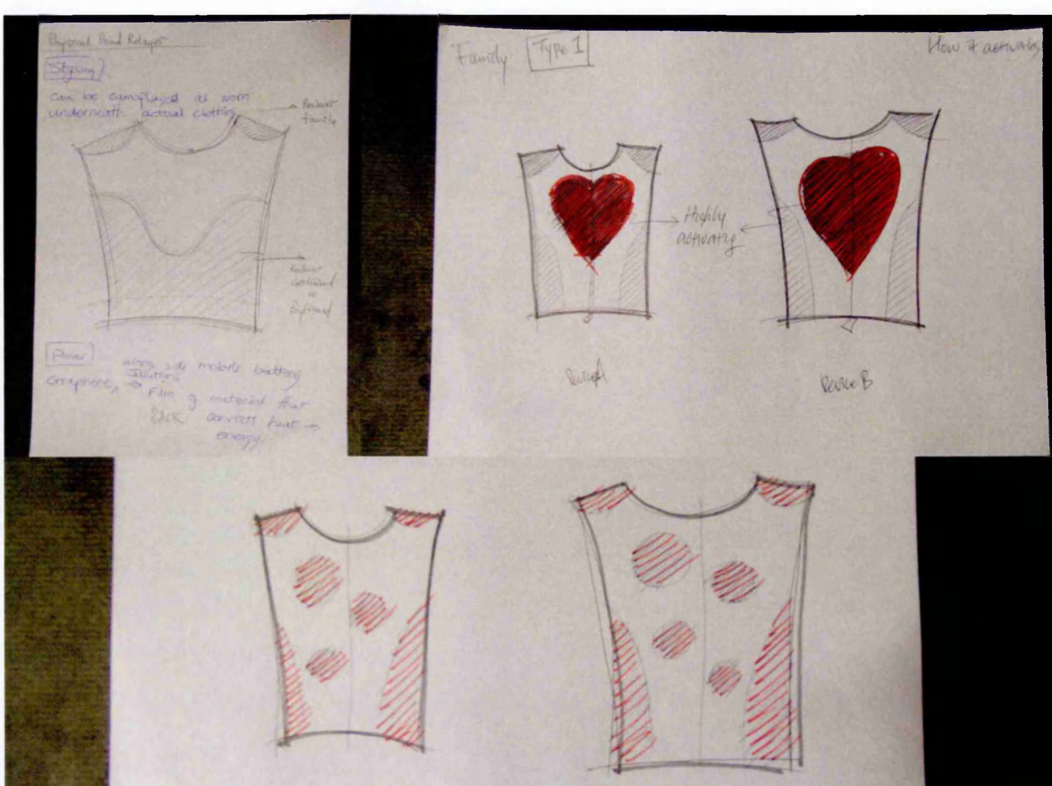


Figure 130: The final design solution in experiment 12 was presented in a series of drawings.

Connectedness

Analysing the degree of connectedness, experiment 12 shows an inconsistent pattern of collaborative design activities (Figure 131). At the beginning of the design process, the total scores seem to be higher than towards the end. The values 8 and 9 are being calculated in segments 2 and 3. In the last two segments the lowest scores of in this experiment, 5 and 4, are being recorded. While the early phase of the design process shows a high degree of connectedness, the nature of collaborative design activity changed gradually in the middle of the experiment. In segment 5, for example, the motional activity got less symmetrical and the linkage of design moves got weaker. Segment 6 showed the same characteristics. In segment 7 and 8, the last two segments, the values dropped to the lowest values of this experiment, i.e. to a very low degree of connectedness.

Experiment 12: Degree of Connectedness per Observational Segment

	0-5 Min	5-10 Min	10-15 Min	15-20 Min	20-25 Min	25-30 Min	30-35 Min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	2	2	3	2	2	2	2	2
Ratio of contributed ideas/design moves	2	3	3	1	3	3	1	1
Degree of linkage between ideas/design moves	2	3	3	2	2	1	2	1
Degree of connectedness	**6**	**8**	**9**	**5**	**7**	**6**	**5**	**4**

(Lowest value: 3, highest value: 9)

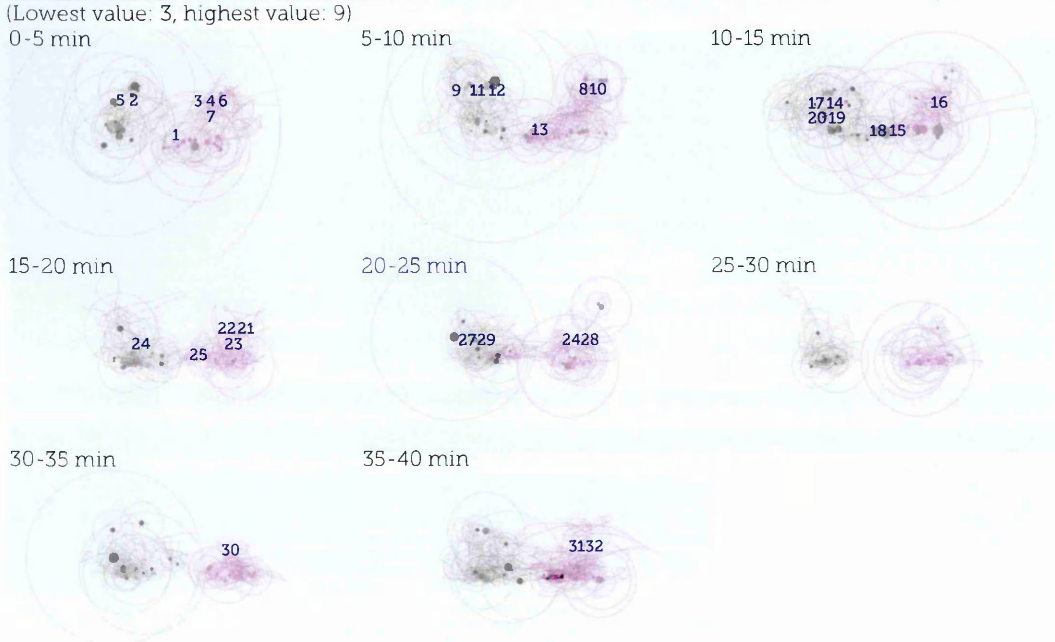


Figure 131: Evaluation matrix for the degree of connectedness and PMTAs of experiment 12.

The place where the ideas or design moves originated from does somewhat reflect the inconsistent pattern of the overall design activity. In accordance with the general separated patterns of motion traces seen in the PMTAs of this experiment, the ideas emerged in their majority from within the personal spaces. In the earlier segments however, some of the design moves seemed to be inspired by the activity taking place in the interpersonal space. This, however, was not the case in segments 5, 6, 7, and 8. Thus, the gradual change of the nature of collaborative activity indicated by the scores calculated, were echoed in the PMTAs as well.

Summary of experiment 12

Experiment 12, using only the sketching condition, shows a design process that is characterised by its increasing degree of separateness. While the participants mutually explored possible design directions in tentative design moves, once starting to sketch the contribution of design moves decreases dramatically. Sketching only started after the participants explicitly agreed to a specific design idea towards the end of the brainstorming phase. Notably, sketching only occurred within the personal space of each participant. Towards the end of the design process, the discussion was replaced by monologue, with the participants having split up to each sketch her and his own variation of the design idea – presenting two different solutions of the same basic design idea. Measuring the connectedness of the design activity, these observations could be corroborated. The highest score was recorded just before the participants started to sketch, and the lowest score at the very end of the design process.

This example documented the observed design activities in an experiment using sketching as a prototyping medium. The next example will investigate whether these observations can also be made in other experiments, using the sketching-only condition.

6.3.5 Experiment 16: separated collaboration

Similar to experiment 12 analysed above, experiment 16 illustrates a case of a separated collaboration. The participants were allowed to use only sketching as a prototyping medium. As in the previous experiment, Figure 132 shows the participants' motional activity remaining within their individual spaces. Until the very end of the task, the participants used the interpersonal space only very sparsely. Over the duration of the experiment, many different ideas were uttered. However, more of them were being proposed by participant B, contributing 15 concepts, while participant A expressed 9 ideas. This was in accordance with the activity that could be traced. The proxemic motion trace analysis shows that participant A paused in her movements significantly more than participant B (indicated by dots and circles). Furthermore, participant B's motion traces seemed to be more intense and focused. This observation in the motion trace analysis reflects the actual split of tasks between the participants, with participant B doing all the sketching work.

Sketching was first used after around 6 minutes. Interestingly, it was only used briefly. The actual main sketching activity seemed to start only after 21 minutes. Notably, after 26 minutes, 5 minutes after the main sketching activity had begun, the participants wanted to use Lego. They had to be reminded that they were only allowed to use sketching for the main task of this experiment. However, their notion to turn to a three-dimensional material might indicate that they perceived limitations in the sketching activity, which could be overcome by using Lego.

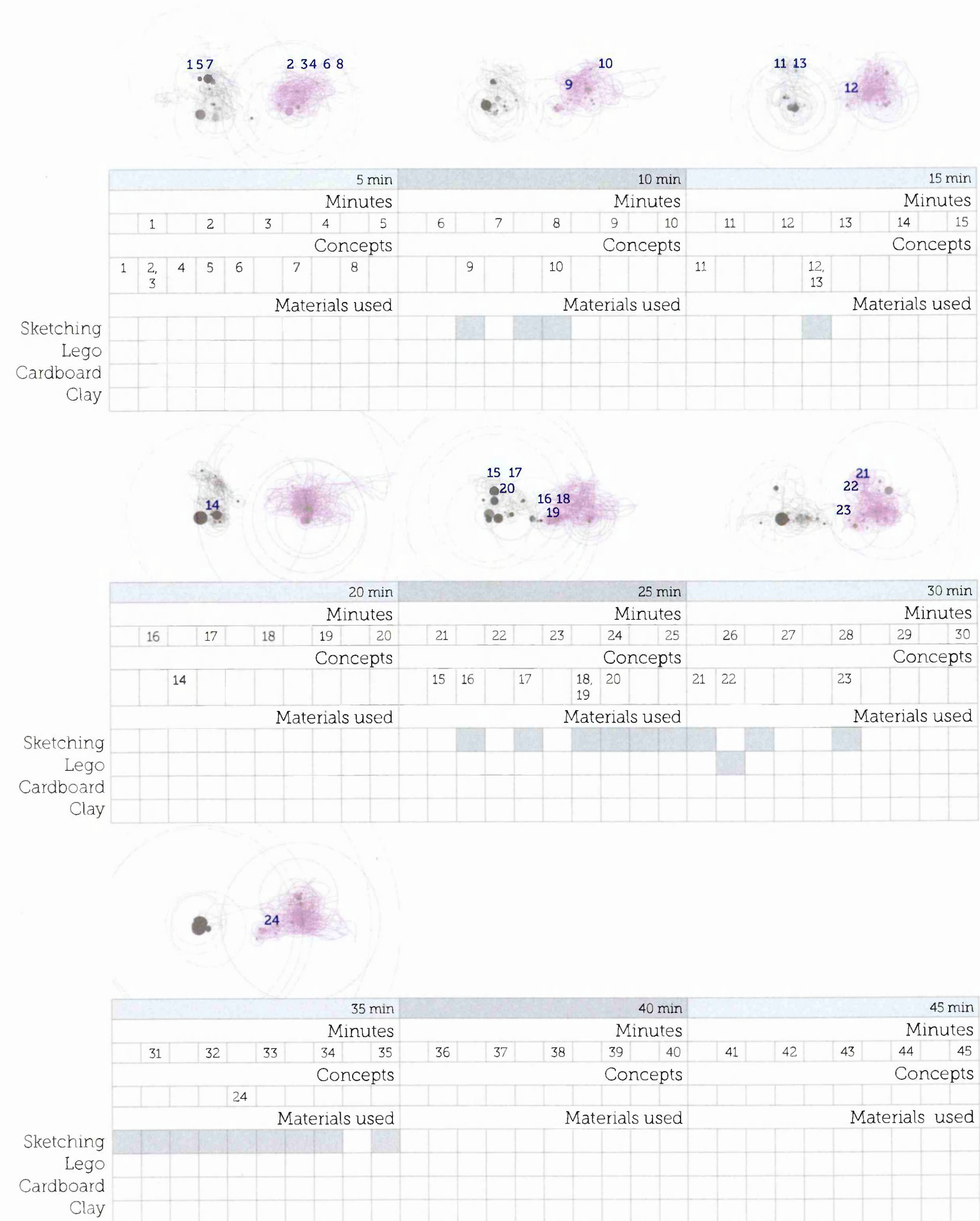
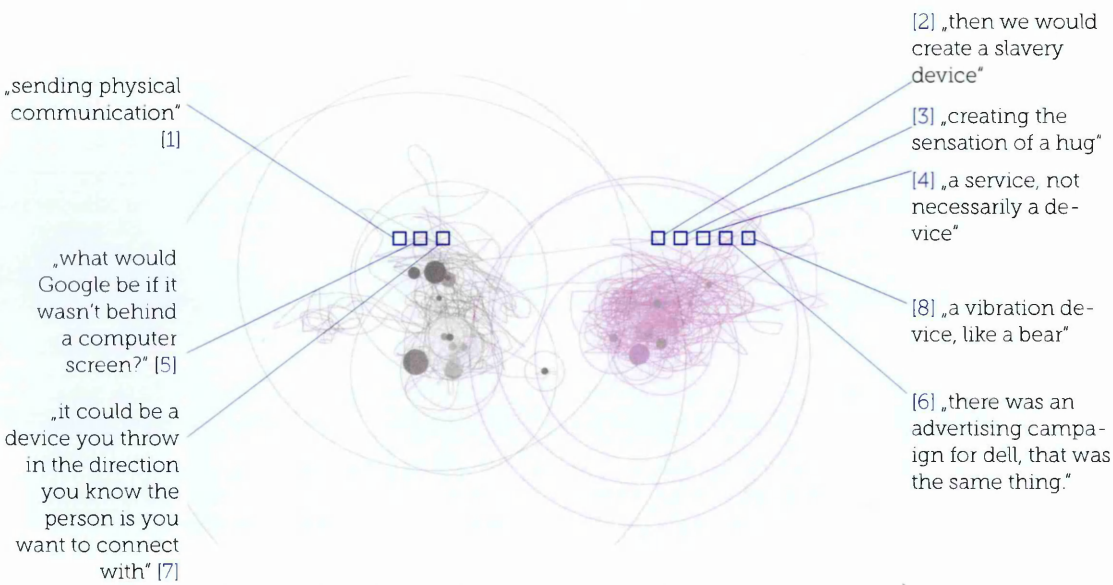


Figure 132: Emergence of ideas and concepts in experiment 16.

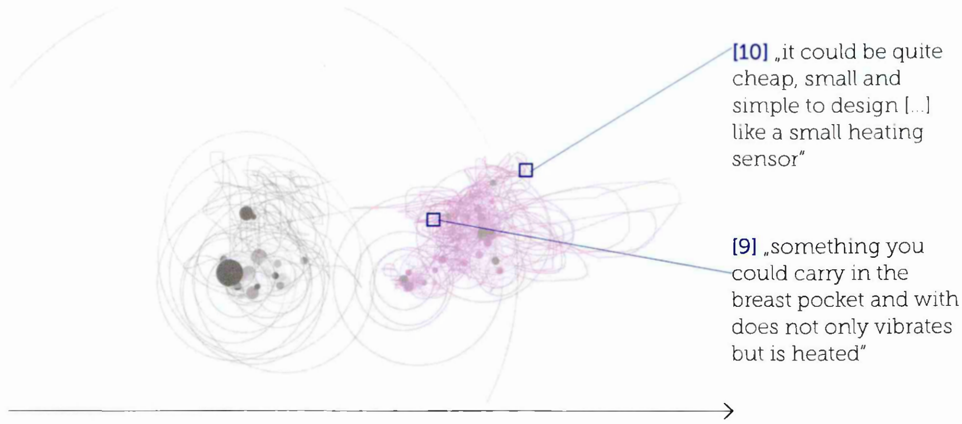
When looking at where the ideas emerged over the duration of the task, another noticeable observation could be made. Most of the ideas emerged right at the beginning of the task within the first five minutes. All of them occurred without using any prototyping material, two- or three-dimensional. The ideas were expressed only verbally. Figure 133 shows the location of the focus of attention of the two participants when the ideas were expressed. The ideas expressed represent a broad spectrum of different possible directions for the design solution.



Time	00:30	01:00	01:30	02:00	02:30	03:00	03:30	04:00	04:30	05:00
Concepts/ Ideas	1	2,3	4	5	6		7		8	
Materials used _Sketching _Lego _Cardboard _Clay										

Figure 133: Design moves occurring in experiment 16 during the first five minutes.

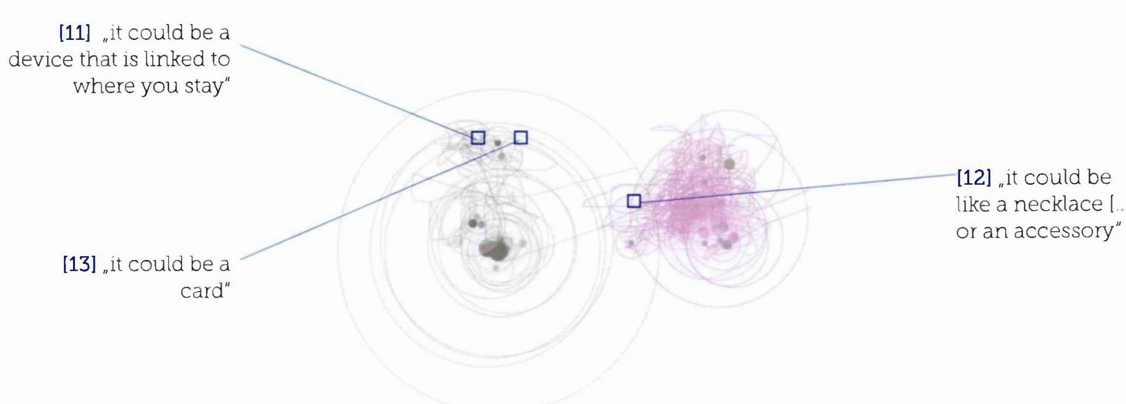
In figure 134, sketching is used for the first time in this experiment. The motion traces of the participants still remain very much in their personal spaces.



Time	05:30	06:00	06:30	07:00	07:30	08:00	08:30	09:00	09:30	10:00
Concepts/ Ideas			9			10				
Materials used _Sketching _Lego _Cardboard _Clay										

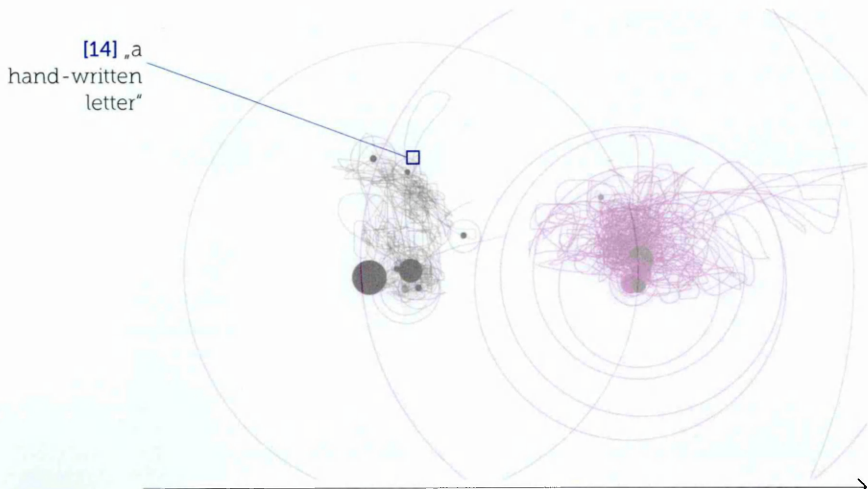
Figure 134: Design moves occurring between minutes 5-10 in experiment 16.

The observation made in the figure above was repeated in the figures 135 and 136. Interestingly, only few contributions were expressed by both participants in these segments.



Time	10:30	11:00	11:30	12:00	12:30	13:00	13:30	14:00	14:30	15:00
Concepts/ Ideas	11				12, 13					
Materials used _Sketching _Lego _Cardboard _Clay										

Figure 135: Design moves occurring between minutes 10-15 in experiment 16.



Time	15:30	16:00	16:30	17:00	17:30	18:00	18:30	19:00	19:30	20:00
Concepts/ Ideas			14							
Materials used _Sketching _Lego _Cardboard _Clay										

Figure 136: Design moves occurring between minutes 15-20 in experiment 16.

In the middle and second part of the task, the main sketching activity took place. The ideas expressed in these sections, between minutes 21 and 28, seemed to be inspired more by the sketching activity (Figure 137). Ideas 16, 18, 19 and 23 were all expressed by participant B while sketching. A difference might be discerned in the quality of the ideas expressed as well. Idea 16 proposed a "pre-set number of smells or feels"; idea 18 "plugging a device into the wall, that every 2 minutes sprays something"; idea 19 "some kind of electronic plug-in and vials"; and idea 23 "we could cover the things that happen inside of it".

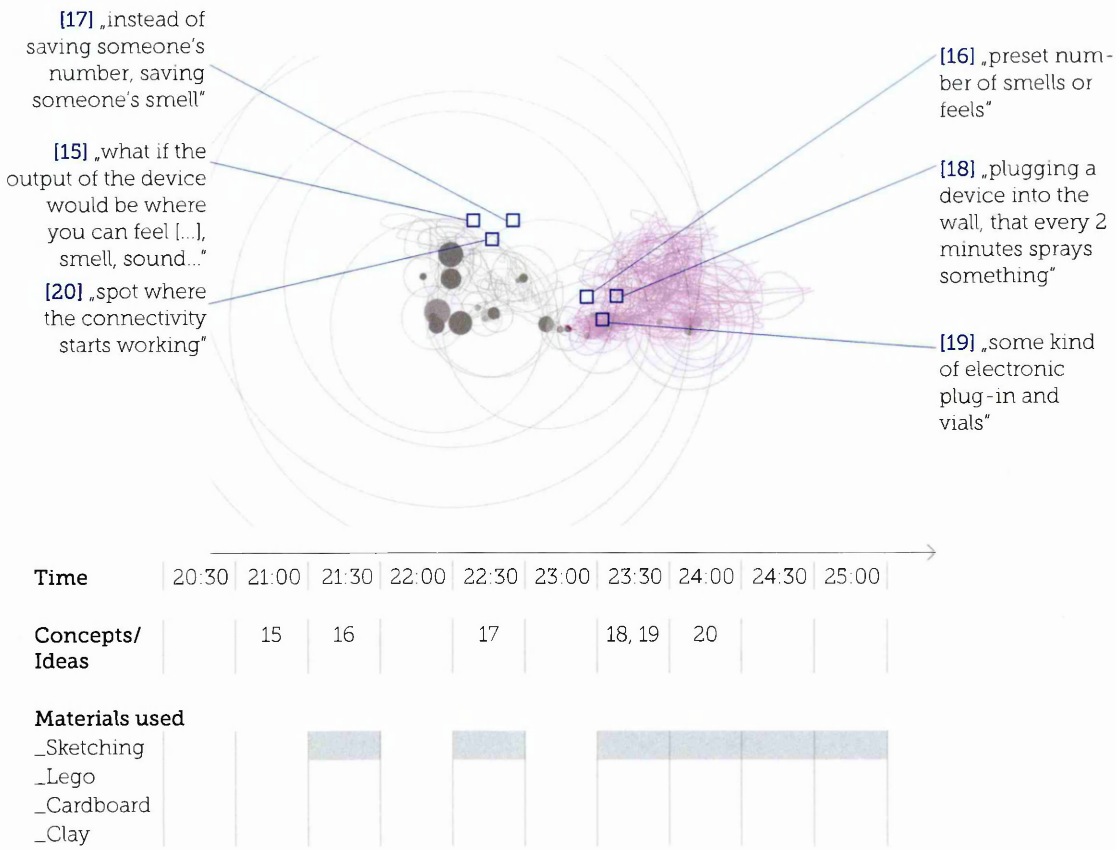


Figure 137: Design moves occurring in experiment 16 between minutes 20 and 25.

Figures 138 and 139 show a tendency of the participant on the right dominating the collaboration by the number of contributions and by the motional activity recorded. Notably, the participants wanted to use Lego in minute 26, but had to refrain from it as they were only allowed to use sketching in this experiment.

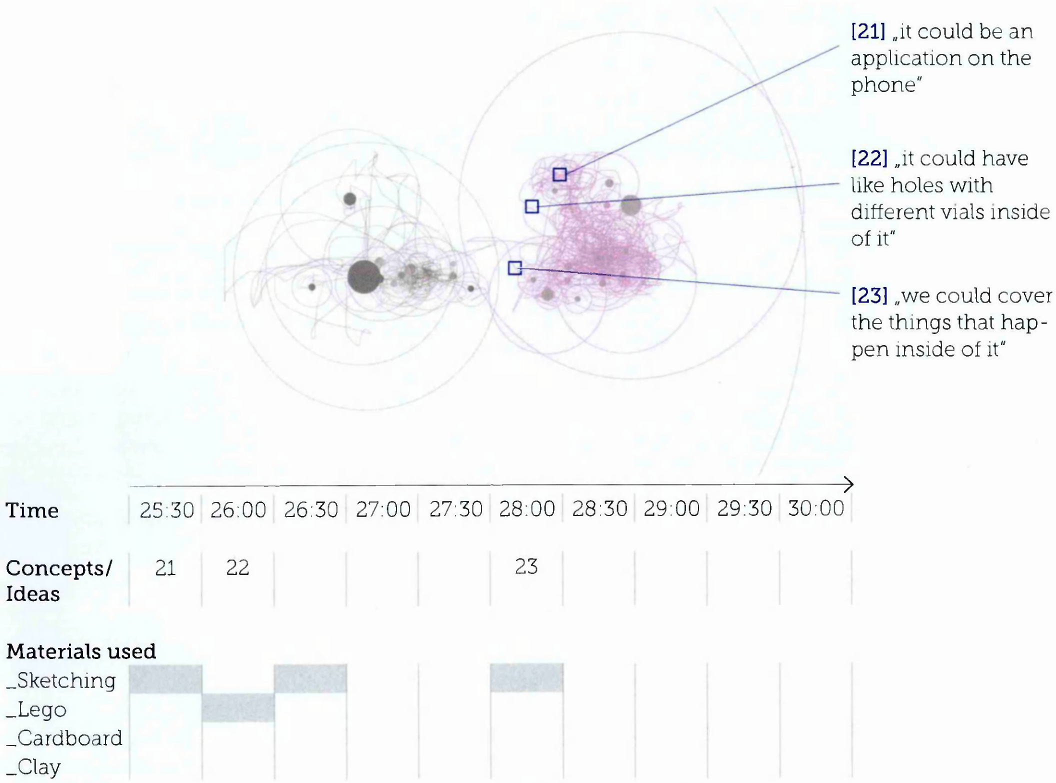


Figure 138: Design moves occurring between minutes 25-30 in experiment 16.

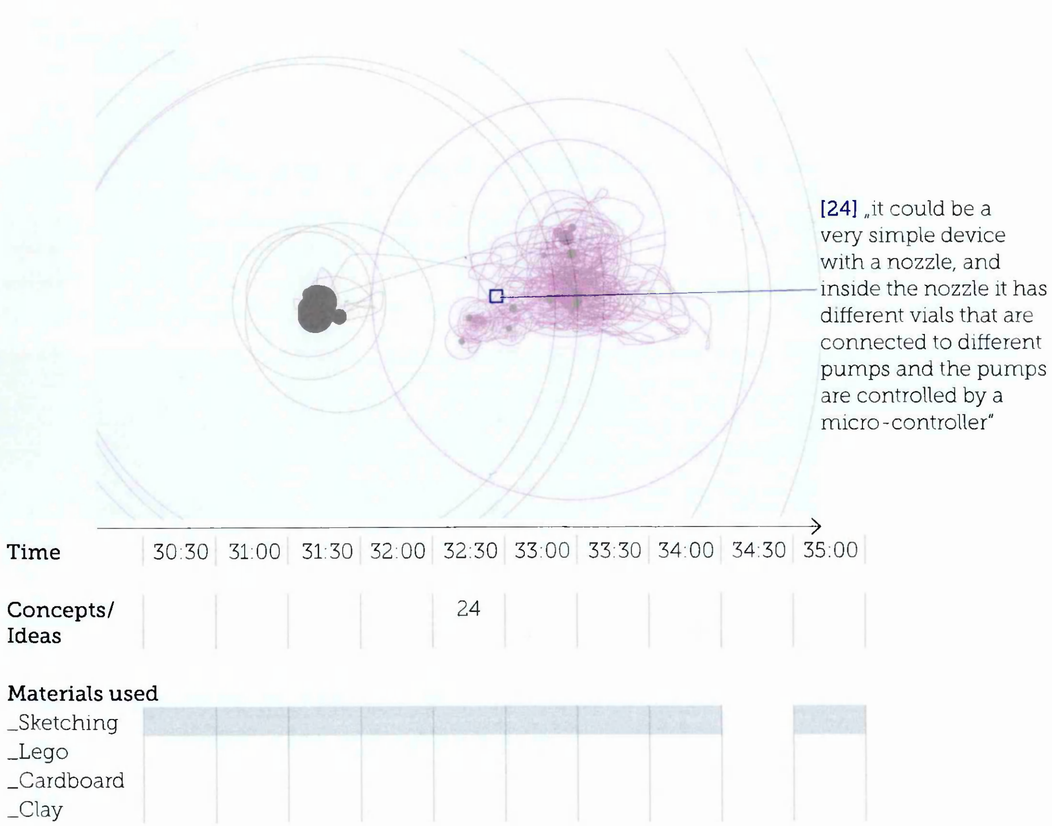


Figure 139: Design moves occurring between minutes 35 in experiment 16.

All of these concepts represent somewhat practical and concrete considerations that move the design solution forward. Comparing these expressions to the ideas contributed by participant A in the same time frame, it appears that they possess a different quality: idea 15 asks "what if the output of the device would be where you can feel [...], smell, sound...?", idea 17 proposes to "instead of saving someone's number, saving someone's smell", and idea 20 a "spot where the connectivity starts working". Taken out of context, it could almost seem that these ideas would occur at different phases in the design task, probably in an earlier stage of the design process. They seem less specific and more concerned with what the design solution should accomplish than the ideas expressed by participant B, whose ideas revolved more around how the solution would actually work and look like (pre-set number, electronic plug-in and vials, covering up the inside).

Another noticeable observation is the tentativeness of expressions throughout the experiment. 'What if?' and 'it could be' are used in almost all utterances, indicating that the participants chose to remain somewhat tentative and not commit to a specific design solution. In the last phase of the experiment, between minutes 30 and 35, the sketching activity is continuous with only one idea expressed by participant B: "it could be a very simple device with a nozzle, and inside the nozzle it has different vials that are connected to different pumps and the pumps are controlled by a micro-controller." The idea expressed in the last two minutes of the design task indicates that participant B was finishing the sketches for later presentation, summarising the most important points of the design solution.

Linkograph

Looking at a combined view of this design task through the lenses of PMTA and linkography (Goldschmidt, 2014), some of the findings can be seen here, too (Figure 140). During the early phase of the design process, in the first 10 minutes, the ideas expressed seem to be only loosely related to each other. There are several interruptions of the connection between the individual ideas. Thus, the character of this exchange of ideas appears to be divergent in its scope, exploring the breadth of possibilities. Noticeably, no prototyping medium was used while exchanging these ideas. During the latter stage of the process, between minutes 20-30, the concepts expressed by the participants seem to be linked to each other more intensively. Ideas 15 to 24 show an uninterrupted line of connection, which might indicate that a specific concept has been developed into more depth. This observation corroborates the observation made earlier regarding the nature of the individual expressions within this time frame. In addition, the focus of attention of participant B (red traces on the right side) tended to shift downwards while using sketching as prototyping medium (between minutes 20-25).

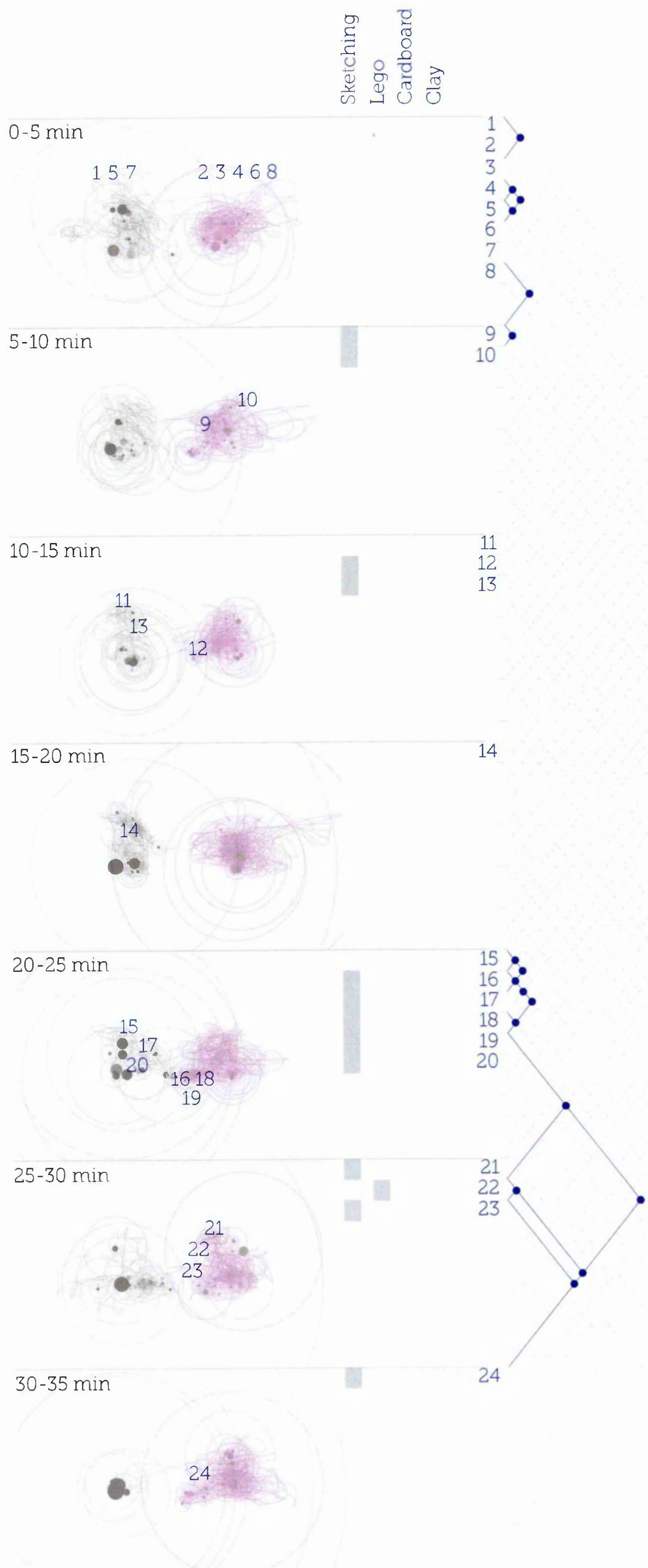


Figure 140: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 16.

Artefacts produced

Taking a closer look at the artefacts, two sketches produced during the completion of the main design task, two observations seem most striking: (1) the sketching and writing seem to have been done mainly, possibly exclusively, by one participant; and (2) the design solution is hardly discernible and remains on a rather non-specific level. These observations are in accordance with the previous analyses, clearly indicating a separated form of collaboration, with one participant seemingly taking over the part of producing the sketches.

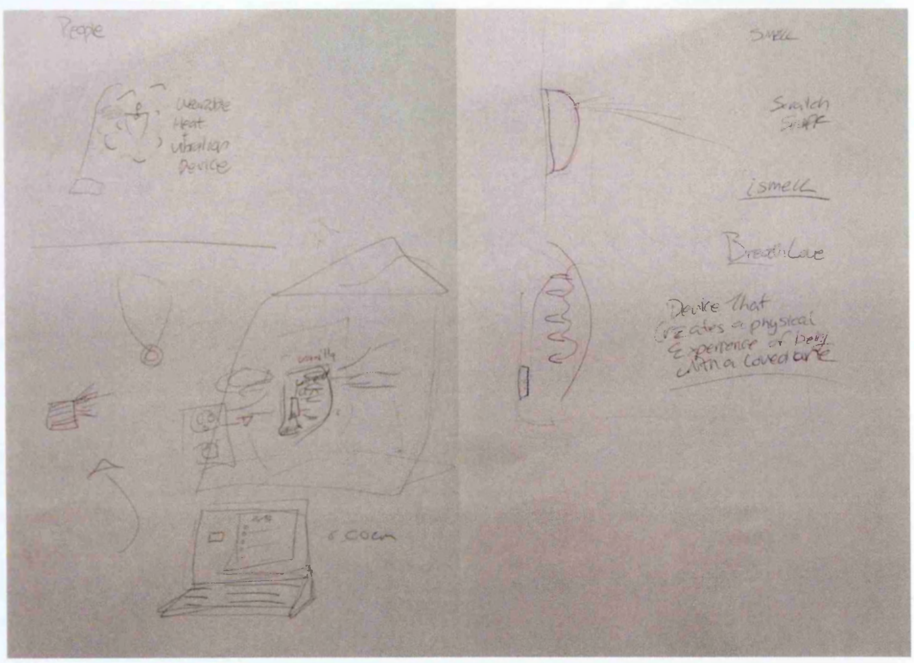


Figure 141: Two sketches produced during experiment 16.

Connectedness

Measuring the degree of connectedness of experiment 16 (Figure 142), the overall picture is that of a very low degree of connectedness. In the last segment, the lowest possible total score of 3 was reached and four times the very low score of 4 was calculated. As seen in the PMTAs of the individual segments, this reflects the separated nature of the motion traces recorded. Furthermore, the number of contributions was biased towards one participant and the individual design moves were only loosely connected.

Experiment 16 | *A Separated Collaboration*

Degree of Connectedness per Observational Segment

	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min	30-35 min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	2	2	1	1	1	1	1	-
Ratio of contributed ideas/de-sign moves	2	1	2	1	3	1	1	-
Degree of linkage between ide-as/design moves	2	1	1	1	2	2	1	-
Degree of connectedness	**6**	**4**	**4**	**3**	**6**	**4**	**3**	**-**

(Lowest value: 3, highest value: 9)

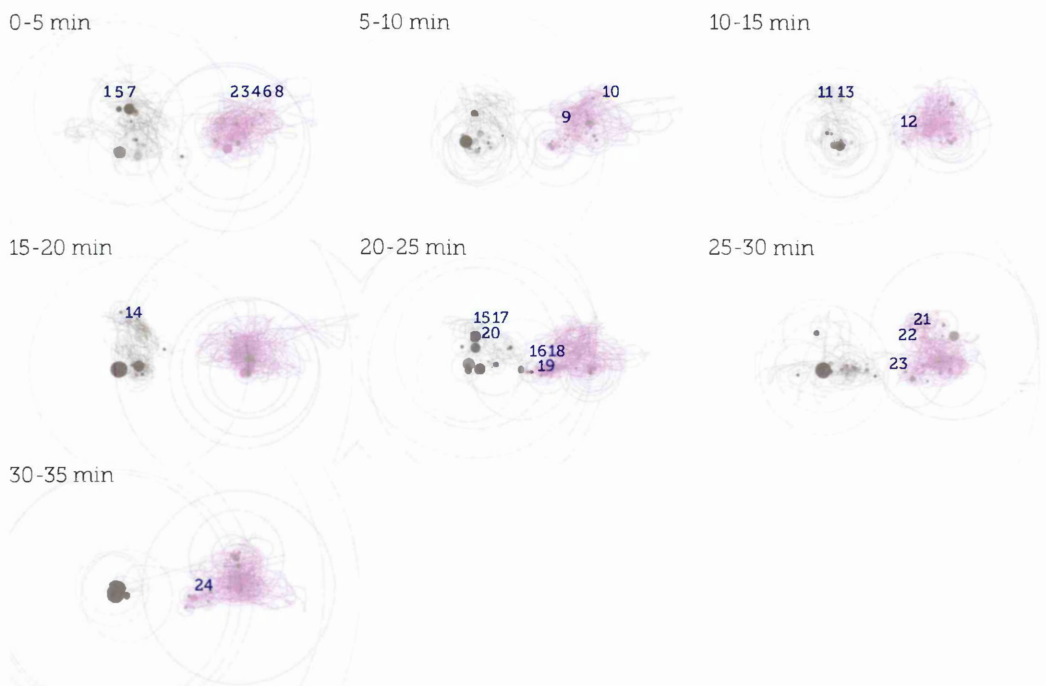


Figure 142: Evaluation matrix for the degree of connectedness and PMTAs of the individual phases of experiment 16.

The first segment, with values of 2 for all three characteristics measured, shows a relatively high degree of connectedness. However, the nature of the collaboration changed over the duration of the experiment. The drop of the values for symmetrical motion traces illustrates that one participant was more active and engaged in the process. The ratio of contributed design moves alternated over the course of the activity, being weak in the beginning, with a peak in the middle of the design process, and being very weak again in the end. This change can also be seen in the nature of the design activity taking place in the individual segments. While in segment 1 both participants were equally engaged, segment 3 was already characterised by a low degree of symmetry and linkage between design moves, but with the participants still both contributing design moves (although they do not seem to be linked). With a peak in segment 5, indicated by a value of 6, the collaborative activity tails off towards the end, with the lowest values in the last segment.

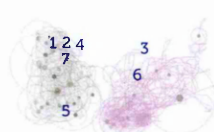
Summary of experiment 16

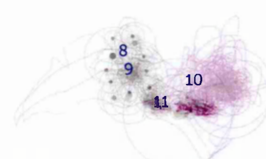
The analysis of experiment 16 tried to see whether the observations made in the previous example, using only sketching as the prototyping medium, could be repeated. This seemed indeed to be the case. Experiment 16 illustrates a case of a separated collaboration, as the participants remained within their personal spaces as well as only one participant appeared to sketch. Measuring the degree of connectedness also showed very low scores, indicating a very unconnected collaboration overall. Notably, most ideas emerged during brainstorming. The sketching activity itself did not spark new ideas, which might be one reason the participants wanted to use Lego after 26 minutes. Whether the exclusion of other materials had any demotivating effect could not be determined. The participants did not commit to a specific design idea, which was also reflected in the linkograph showing connected design moves only towards the end of the process.

This experiment supported the observations made so far regarding the sketching condition. The next example will look more closely at what happens when sketching and three-dimensional prototyping media are used in combination.

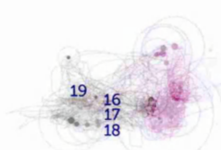
6.3.6 Experiment 19: switching from separated to connected designing

Experiment 19 illustrates an example where the participants moved from a separated collaboration to a connected design activity. Initially, the participants used sketching to develop their design solution but switched to clay after seven minutes into the task (Figure 143). The first five-minute segment of the motion trace analysis shows a very similar picture, as does the analysis of experiment 16. The two participants very much remain with their movements in their individual spaces, not interacting in the interpersonal space at all. Ideas were expressed while sketching, but did not explicitly refer to what was drawn or written down. The number of ideas expressed indicates some sort of brainstorming taking place in this phase of the experiment.





										5 min										10 min										15 min
										Minutes										Minutes										Minutes
		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15
										Concepts										Concepts										Concepts
	1	2	3		4	5			6	7				8		9, 10	11				12		13				14		15	
										Materials used										Materials used										Materials used
Sketching																														
Lego																														
Cardboard																														
Clay																														



										20 min										25 min										30 min
										Minutes										Minutes										Minutes
		1		2		3		4		5		6		7		8		9		10		11		12		13		14		15
										Concepts										Concepts										Concepts
			16				17	18	19																					
										Materials used										Materials used										Materials used
Sketching																														
Lego																														
Cardboard																														
Clay																														

Figure 143: Emergence of ideas and concepts in experiment 19.

The ideas do represent a broad spectrum from "maybe we talk about transmitting warmth", or "there could be a way of communicating through reflection", to "maybe in the pillow there's a burst of fragrance." In minute 8 a key concept is being expressed: "what if you felt a pulse when you put our hand around a mug?" Both participants seemed to agree on this idea and started working with clay immediately afterwards.

Once using clay as prototyping medium, a noticeable change in the nature of the concepts uttered is discernible (Figures 144 & 145). While the former ideas were trying to find a possible path to follow from a wide range of possibilities, the concepts contributed after minute 8 seem much more focused and specific. "There would be this contact here [gesture] and this contact here [gesture]", "then we have almost like sensor points here [sketching]", and "they would do a hand print scan and then it would be manufactured" were concepts expressed right after using clay to model a mock-up mug.

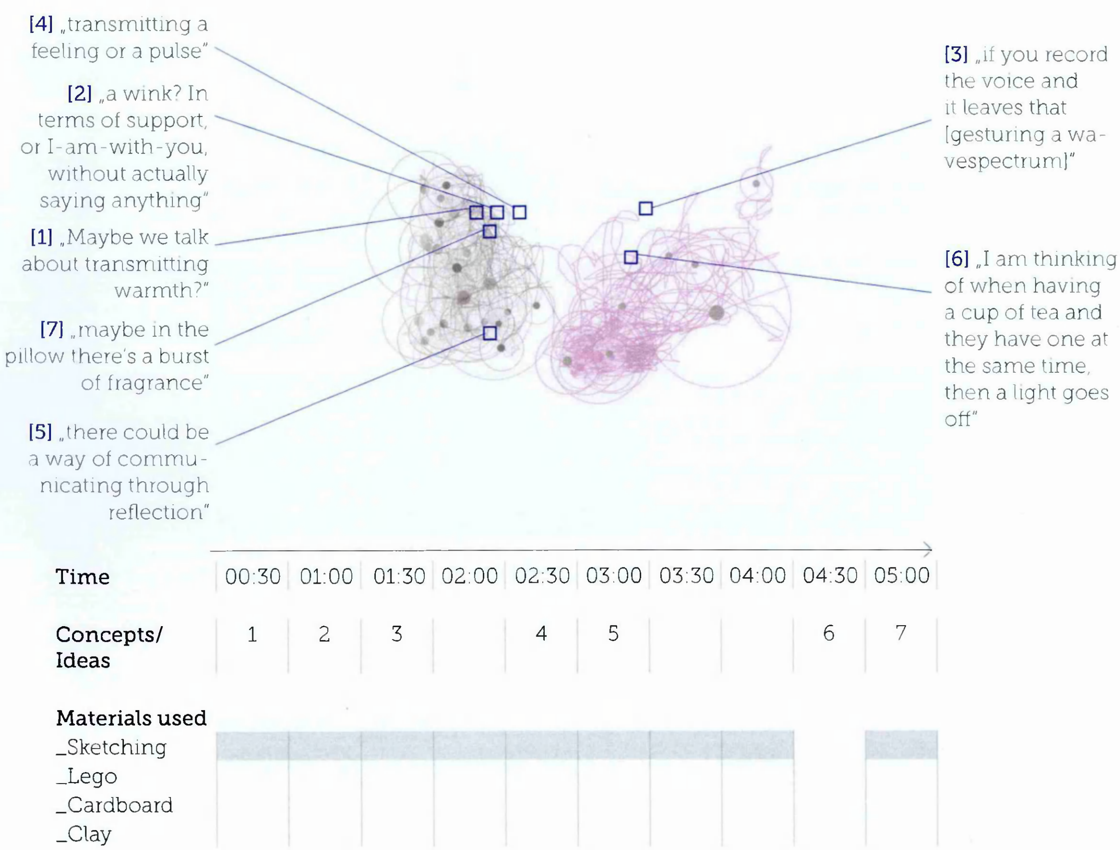


Figure 144: Design moves occurring in the first five minutes of experiment 19.

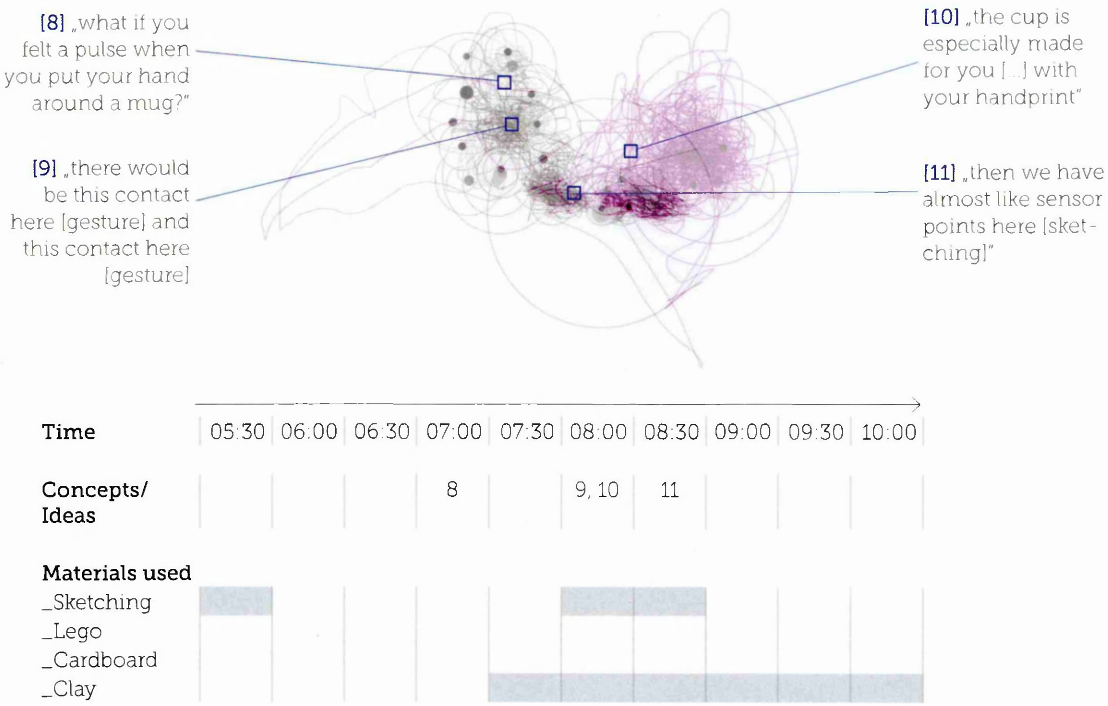


Figure 145: Design moves occurring between minutes 5-10 of experiment 19.

In figure 146 the motional activity recorded was still intense for both participants and the design moves contributed in equal numbers.

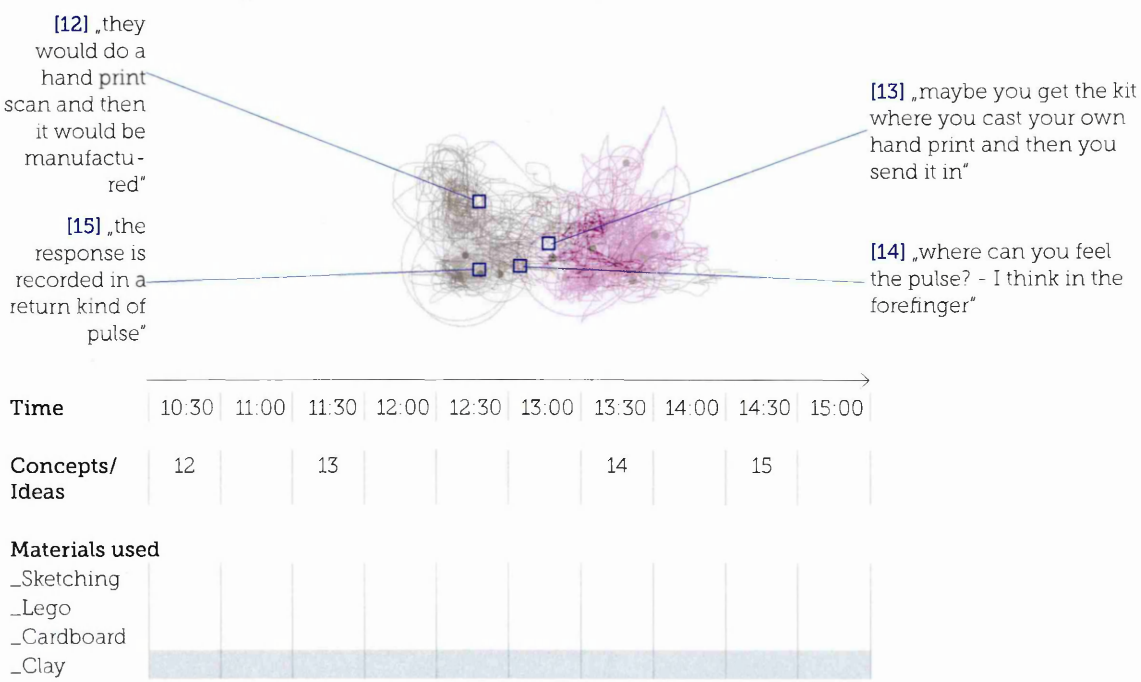


Figure 146: Design moves occurring between minutes 10-15 of experiment 19.

The last segment of this experiment shows an intense activity of proxemic motion, with the participants seemingly to evaluate their design solution towards the end (Figure 147).

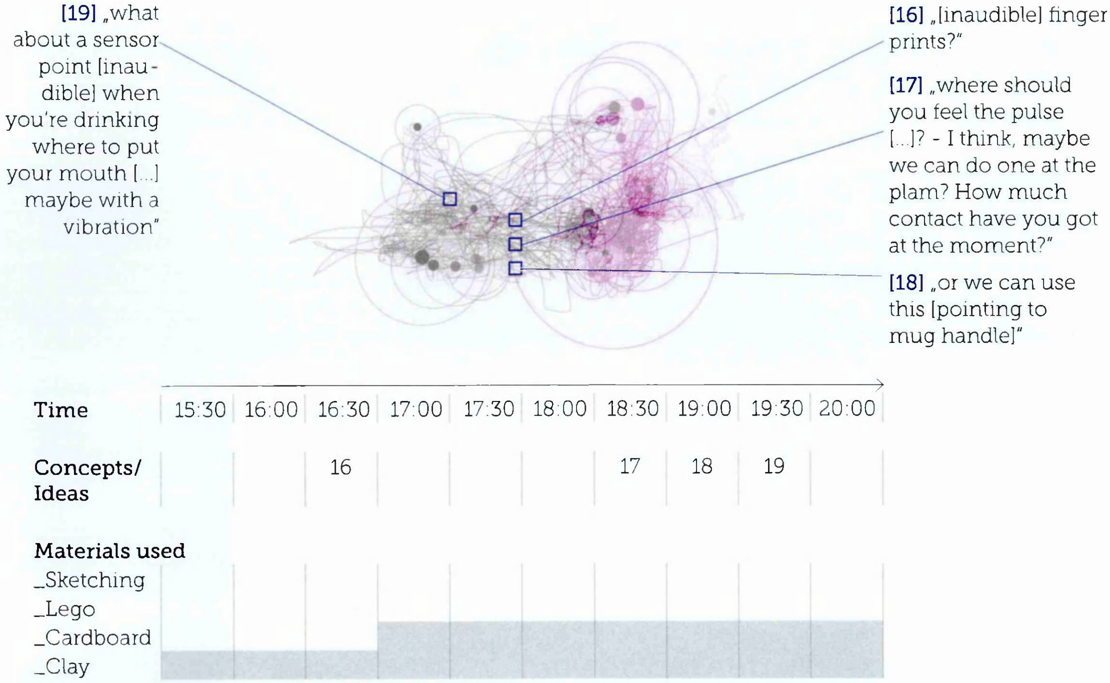


Figure 147: Design moves occurring between minutes 15-20 of experiment 19.

After starting prototyping with clay, the ideas continuously emerged throughout the rest of the experiment without changing the nature of the ideas contributed. In addition, ideas emerged more from the collaborative work of the participants. In minute 14, one participant asks, "where can you feel the pulse?" with the other replying "I think in the forefinger." In minute 24 as well, a collaborative verbal interaction is taking place, with participant A asking "where should you feel the pulse [...]?", and participant B replying "I think, maybe we can do one at the palm? How much contact have you got at the moment?" With switching to using clay after eight minutes into the task, the interpersonal space between the participants was used much more intensively. The motion trace analysis shows a quick development of the individual hand movements towards each other and a focus on the shared space on the table (the lower part of the diagrams). A direct comparison of the movement taking place in each 5-minute segment of the experiment illustrates the tendency of the collaborative work converging in the interpersonal space once using clay as the prototyping medium (Figure 148-151).

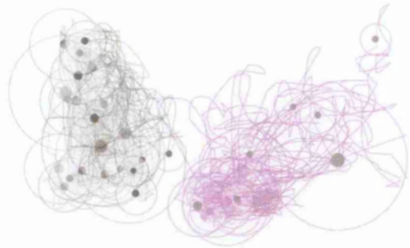


Figure 148: Hand movements occurring between 0-5 minutes in experiment 19.

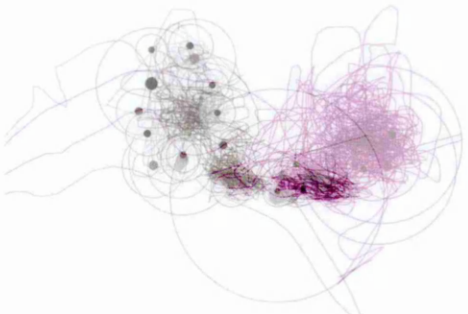


Figure 149: Hand movements occurring between 5-10 minutes in experiment 19.

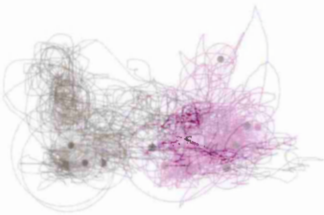


Figure 150: Hand movements occurring between 10-15 minutes in experiment 19.

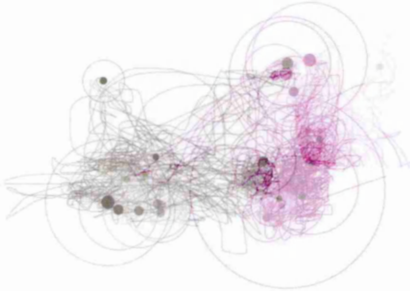


Figure 151: Hand movements occurring between 15-20 minutes in experiment 19.

Overall, the design process observed in this experiment could be described as moving from breadth to depth. First, a number of different ideas were quickly put forward. Then the participants chose to focus on one particular idea and developed it further. Once a concept was chosen for execution, the progression of the design solution became more and more detailed, as the ideas contributed after the decision imply.

Linkograph

This observation is also discernible when combining the PMTA with a linkograph of the experiment (Figure 152). In the first five minutes, out of seven design moves contributed by both participants, five were orphan moves, not being connected to or followed up by other design moves. The spectrum of ideas expressed during that time segment reflects the approach of collecting diverging ideas. Ranging from transmitting a wink, over a fragrance exuding pillow, to conveying wave spectra, the ideas did not seem to possess a strong connection between them. The turning point in this divergent discussion was design move 8, occurring seven minutes into the experiment. Asking "what if you felt a pulse when you put your hand around a mug?" in a propositional way, this design move linked back to design move 4, which proposed "transmitting a feeling or a pulse". Up to this point, the participants did not agree upon a general direction in which they would develop their design solution. All design moves except one (design move 16) after this turning point are connected to each other. However, in the linkograph of this experiment, design move 16 could not be linked, as its disturbed audio recording ("[inaudible] fingerprints?") did not allow for an interpretation whether or not it might express an idea connecting to the other design moves.

Significantly, once the participants seemed to have agreed to an idea, they turned from using sketching to employing clay. Apart from an increased use of the interpersonal space between them, a change in the nature of the conversational topics could be observed. The triangular web formed by the connected design moves starting at design move 8 indicates that a design issue was thoroughly investigated. This thoroughness is echoed in the recorded contributions of the participants. While the individual expressions have been rather general in the sense of design direction they proposed, the utterances became much more focused and specific after design move 8. Furthermore, the long link span, for example from design move 8 to 19 ("what about a sensor point [inaudible] when you're drinking where to put your mouth"), corroborates the importance of this early idea.

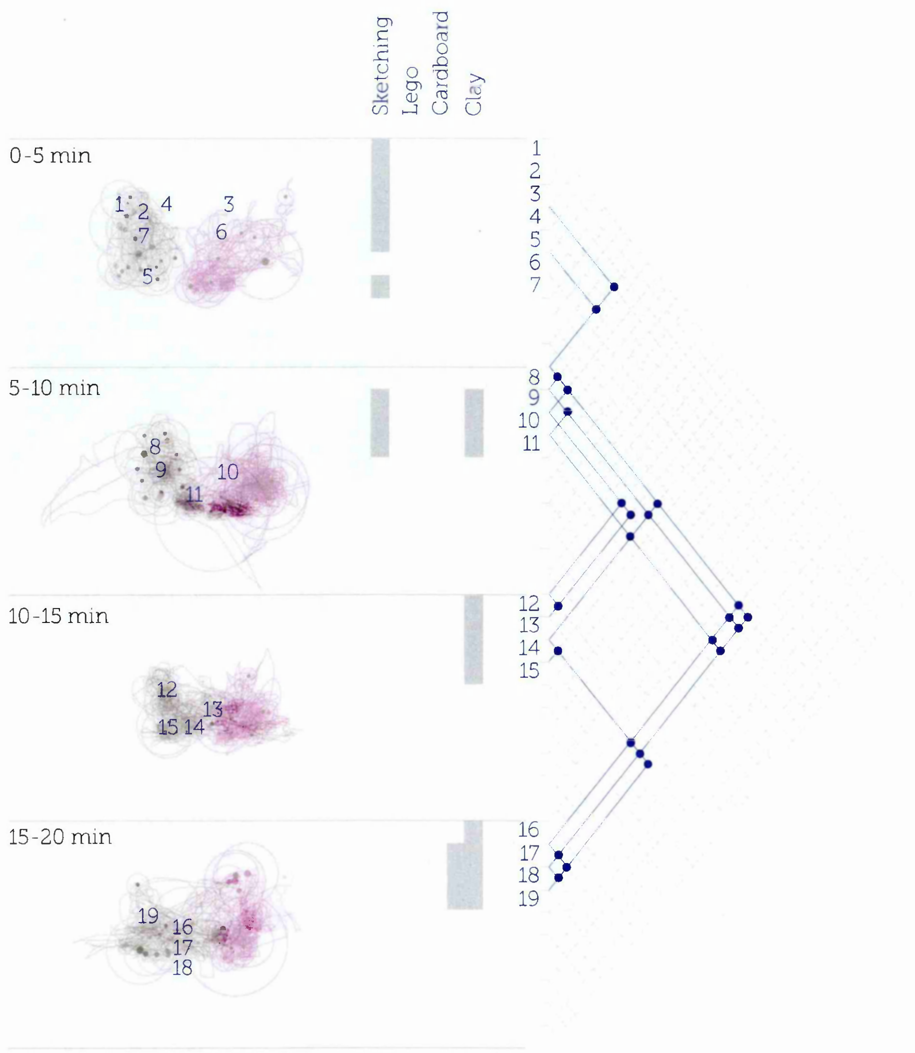


Figure 152: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 19.

Artefacts produced

The specificity of the discussion occurring when building the mug prototype can be seen in the artefact produced. The mug displays the distinct features that have been considered by the participants, like the 'mouth sensor', the 'fingertip sensors' or the hand imprint in the mug itself. Prototyping predominantly with clay, it seems, too, that next to the functional aspects of the design solution, aesthetic properties were considered: for example, how the handle attaches itself to the body of the mug.

Figure 153: Prototype of an interactive mug produced in example B.

Connectedness

Regarding the connectedness of the collaborative design activities, the scores calculated for experiment 19 (Figure 154) show a completely different picture to experiment 16. Three times out of four, the maximum score of 9 was calculated. Only in two instances in the first segment, the ratio of contributed ideas was slightly biased towards one participant and not all the design moves were connected. This is hardly a surprise, as in the first five minutes the participants usually brainstormed different ideas and began to get a grasp of the task. The scores appear to be echoed in the PMTAs as well. Apart from the first segment, the recorded motion traces show quite symmetrical patterns and intensities. While there is a slight bias in the ratio of contributed design moves towards one participant in the very first segment, this balances itself rather quickly. Thus, the design activity occurring in this experiment shows a high degree of connectedness.

Summary of experiment 19

In experiment 19, the participants move from sketching to using clay. Sketching was used predominantly in the first 5 minutes of the design process. The type of expressions recorded during that phase indicated that it was probably used as a notation of the ideas expressed while brainstorming. The main concept emerged in minute 8, after 1 minute of using clay.

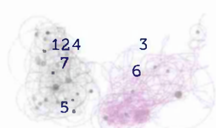
Experiment 19 | *Switching form Separated to Connected Designing*

Degree of Connectedness per Observational Segment

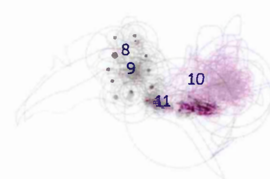
	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min	30-35 min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	3	3	3	3	-	-	-	-
Ratio of contributed ideas/design moves	2	3	3	2	-	-	-	-
Degree of linkage between ideas/design moves	2	3	3	3	-	-	-	-
Degree of connectedness	**7**	**9**	**9**	**8**	**-**	**-**	**-**	**-**

(Lowest value: 3, highest value: 9)

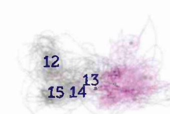
0-5 min



5-10 min



10-15 min



15-20 min

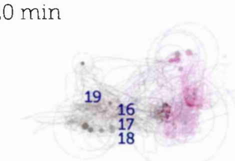


Figure 154: Evaluation matrix for the degree of connectedness and PMTAs of the individual phases of experiment 19.

Once using the three-dimensional prototyping medium, expressions became more specific and the motional activity started to converge in the interpersonal space between the participants. In addition, the ideas emerged throughout the process while using clay. The linkograph shows how the process moved from breadth to depth, with all design moves connected once the brainstorming phase was finished. Measuring the degree of connectedness, the activity could be classified as highly connected. The lowest score, 7, was recorded right at the beginning, with the maximum scores in the following segments.

This experiment illustrated the combined use of sketching and clay to develop a design solution. The last example will compare these observations with a design process where all prototyping materials were used.

6.3.7 Experiment 22: connected designing

Experiment 22, like the previous example, represents a case of connected designing. The two participants in experiment 22 used all four prototyping media provided: sketching, Lego, cardboard and clay (Figure 155). In contrast to experiment 19, use was made of the three-dimensional prototyping media, especially cardboard, almost from the start.

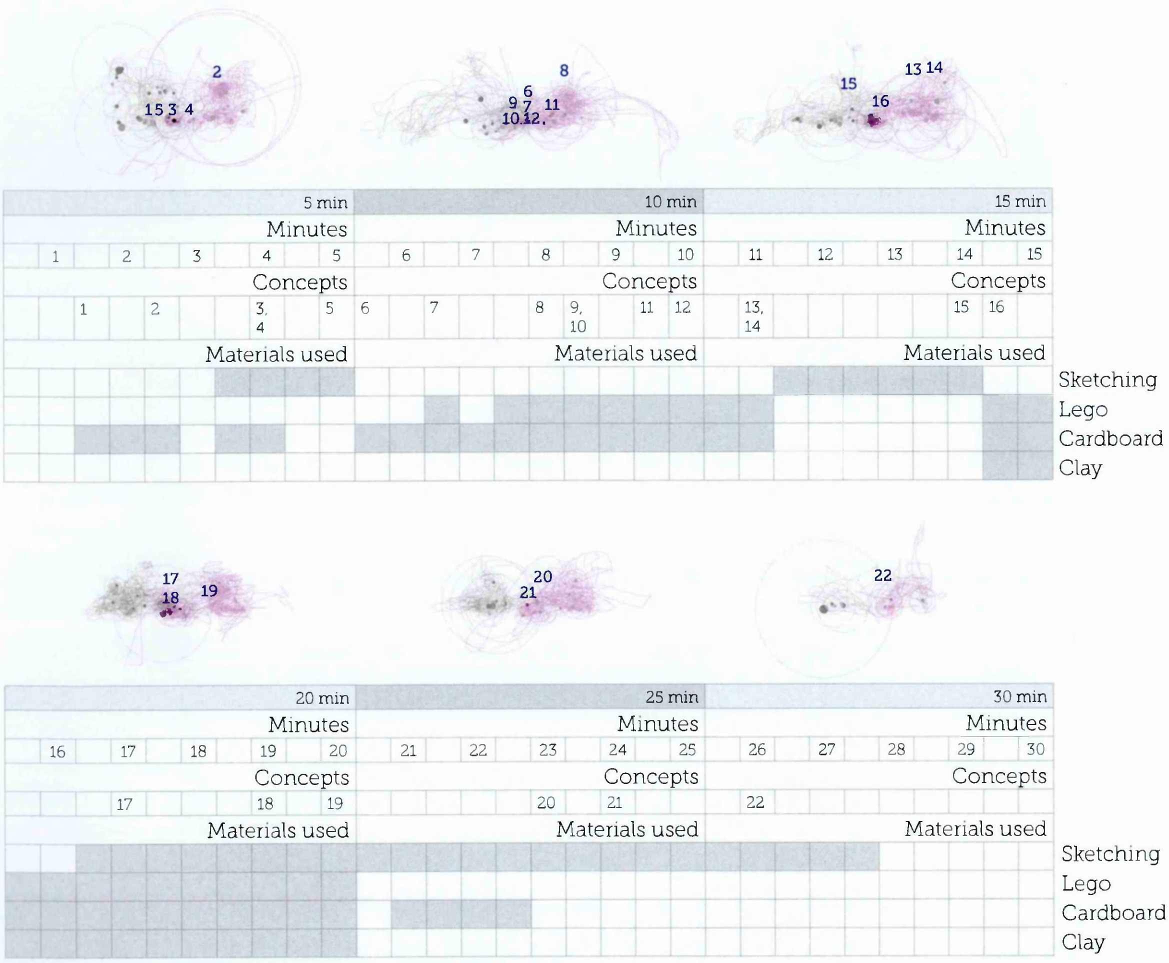


Figure 155: Emergence of ideas and concepts in experiment 22.

In a general observation, the analysis reveals a difference in the level of symmetry and intensity between the phases where the three-dimensional prototyping media were used to the phases where sketching was used. The motion trace analysis of minutes 5 to 20 indicates a quite symmetric distribution of movements between the participants with intensive use of the interpersonal space. This is in contrast to minutes 20 to 30, where the participants using sketching were not equally engaged in the designing process. The motion traces on the left side have significantly more pauses than the ones on the right side, suggesting that only one participant was engaged in the sketching activity.

The very first idea was inspired by a piece of cardboard in the size of a credit card. Participant A proposed "a holographic colour receiver [...] could be in the form of a card". This original idea was agreed upon also by participant B, and subsequently the discussion moved quickly into more detail with details of the design solution being proposed as soon as four minutes into the experiment. Remarks like "So the camera should be here and then [...] we have the buttons here" or "How thick would it be? Should we use this [holding up a piece of cardboard]?" indicate the level of detail the design discussion was engaged in as early as five minutes into the experiment (Figure 156).

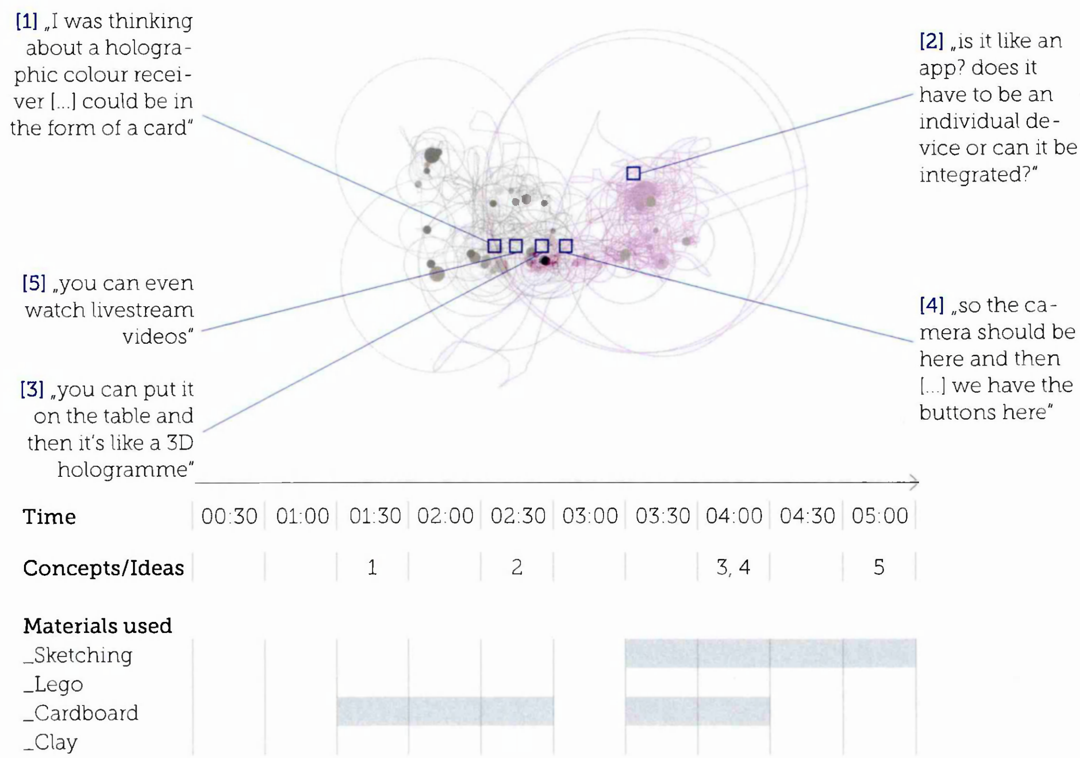


Figure 156: Design moves occurring between minutes 0-5 of experiment 22.

After six minutes, Lego is also being used in combination with cardboard inspiring another key concept emerging soon afterwards, expressed by the question: "what if it's like a watch?" (Figure 157).

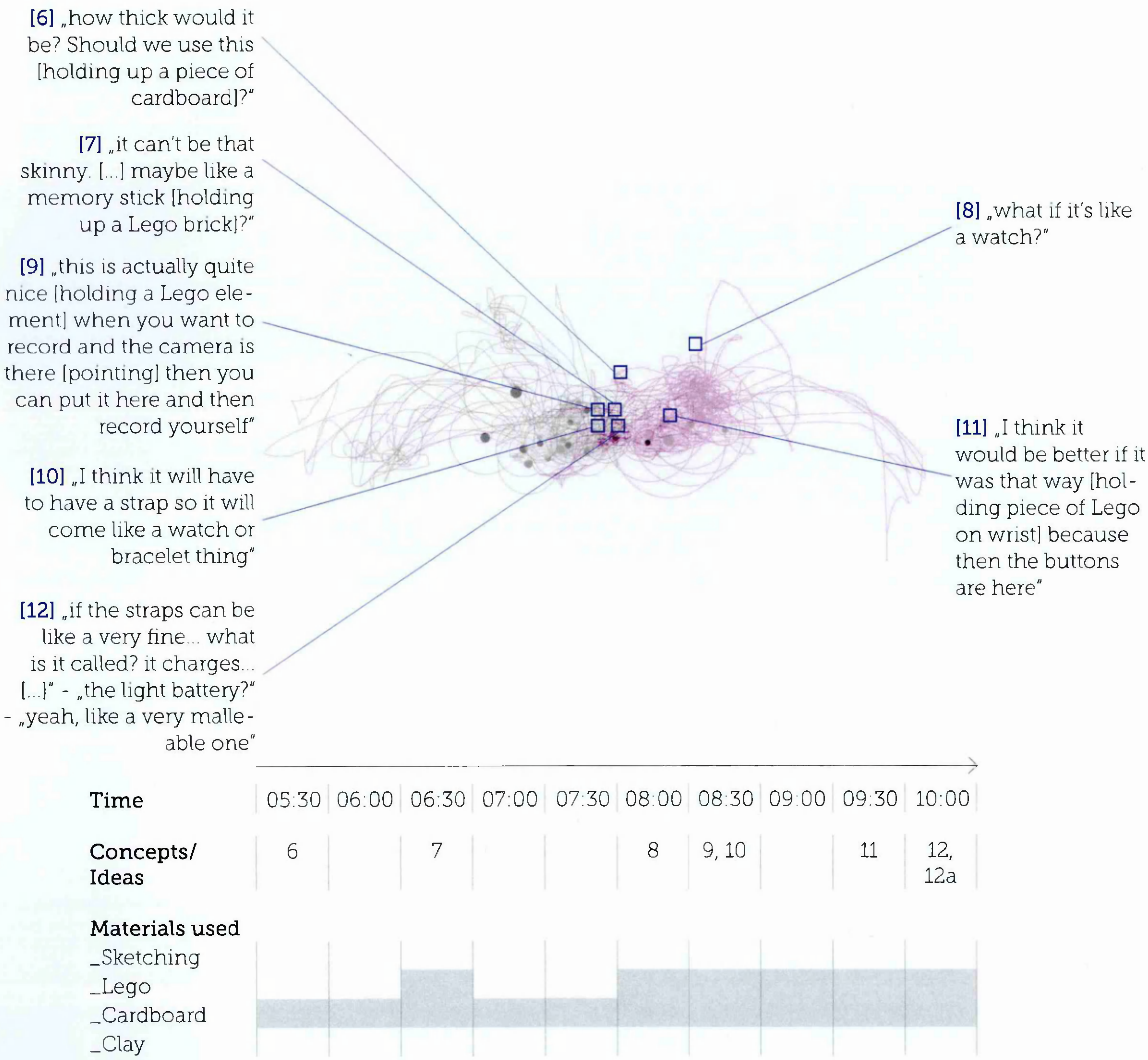
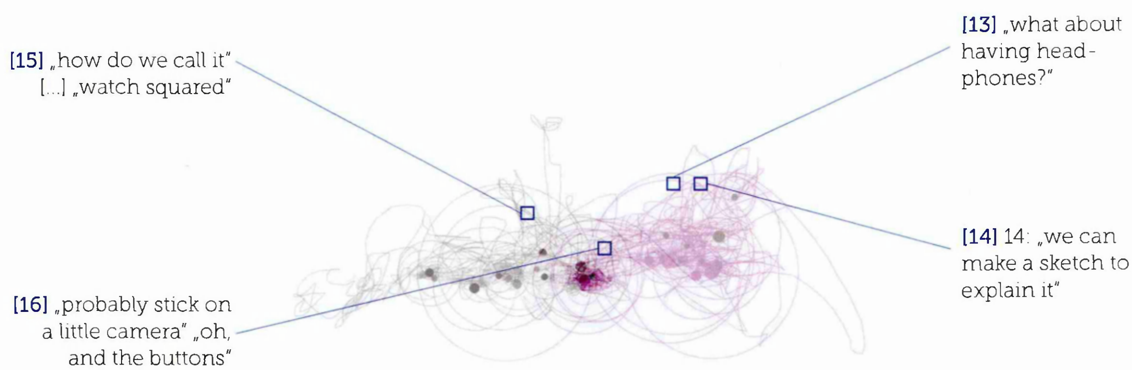


Figure 157: Design moves occurring between minutes 5-10 of experiment 22.

Sketching is used after 11 minutes, noticeably not as a prototyping medium, but as a form of presentation or description. Participant B proposes to "make a sketch to explain it." Subsequently, one participant engages more in sketching the individual features of the design solution for representational purposes while the other works out details on the mock-up watch (Figure 158). However, on different occasions the participant sketching would interact with the three-dimensional model, too, and contribute possible improvements to the design solution like: "The Lego needs to be this way [pointing] so you can reach the buttons". The analysis shows that most ideas were exchanged in the time Lego and cardboard were used, between 5 and 11 minutes into the experiment.



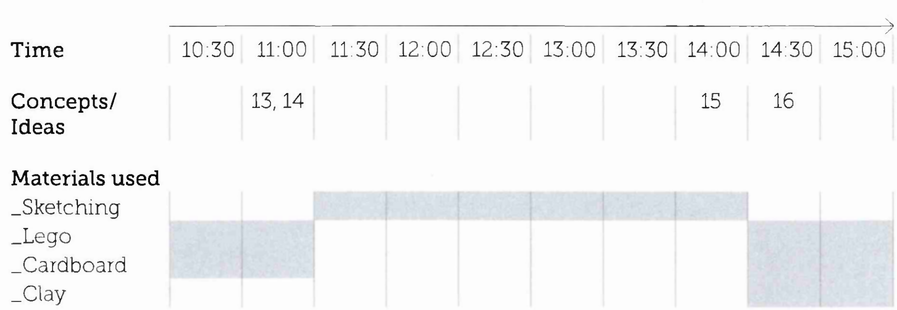


Figure 158: Design moves occurring between minutes 10-15 of experiment 22.

In segment 4 (Figure 159) the participants used all four prototyping media simultaneously.

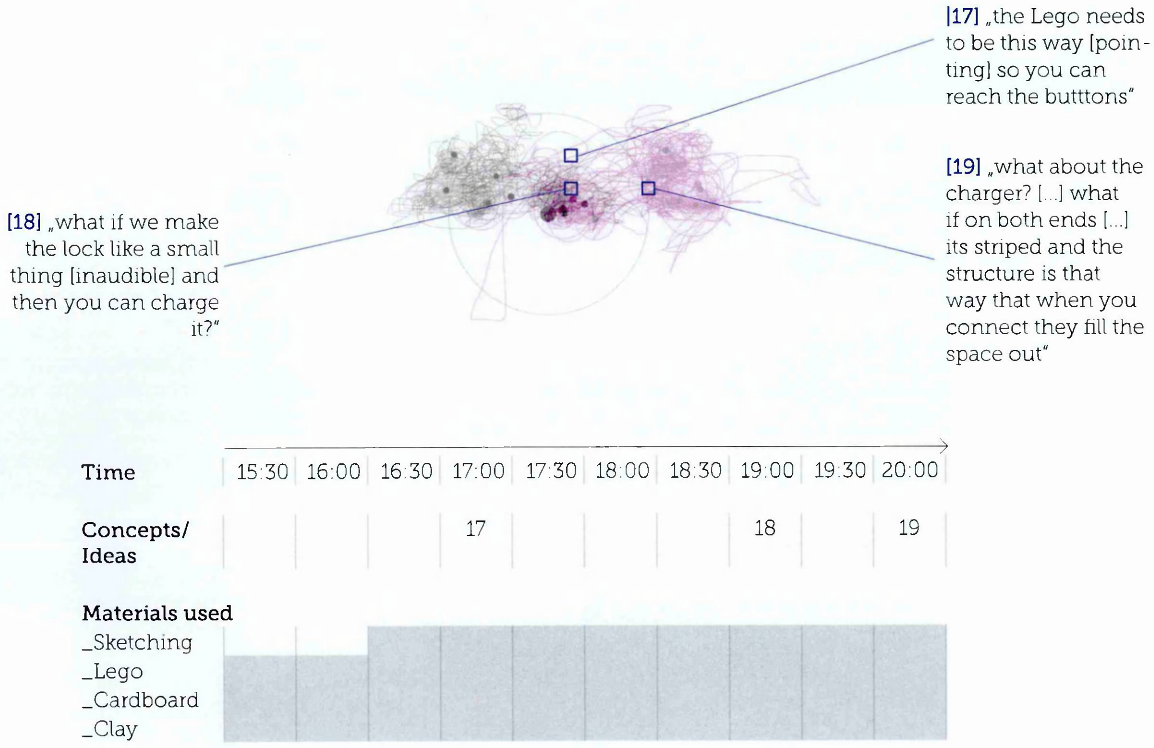


Figure 159: Design moves occurring between minutes 15-20 of experiment 22.

Notably, as in the figure above, the location were the design moves seem to originate is to be found in the shared, interpersonal space (Figure 160).

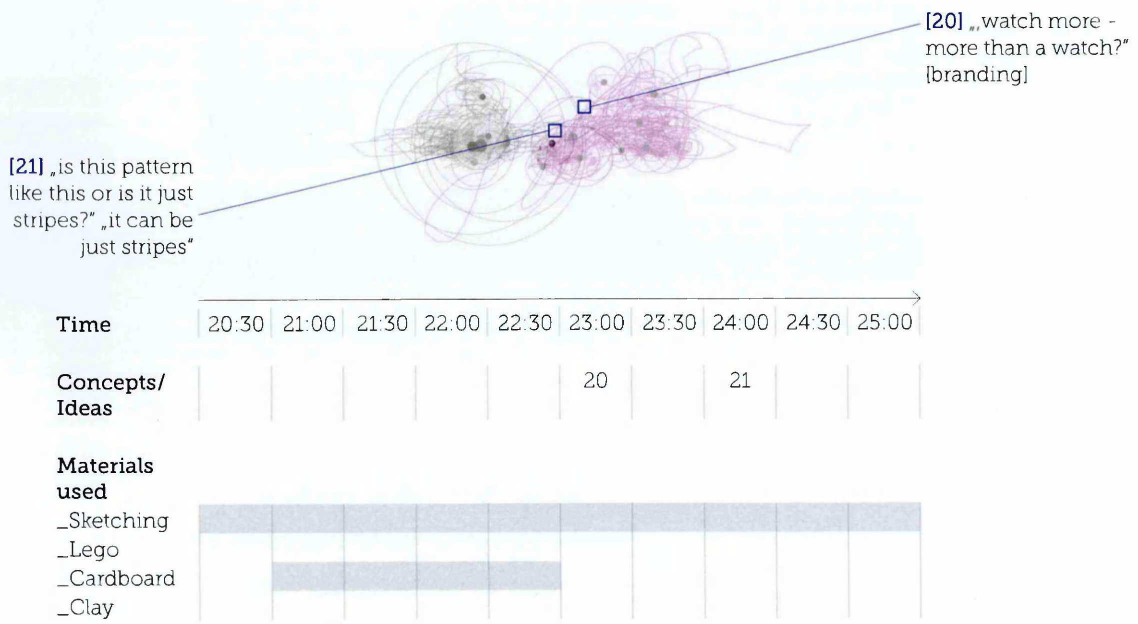


Figure 160: Design moves occurring between minutes 20-25 of experiment 22.

In the last segment (figure 161) the final design seems to be completed in minute 27. The last design move contributed relates to the naming of the design solution.

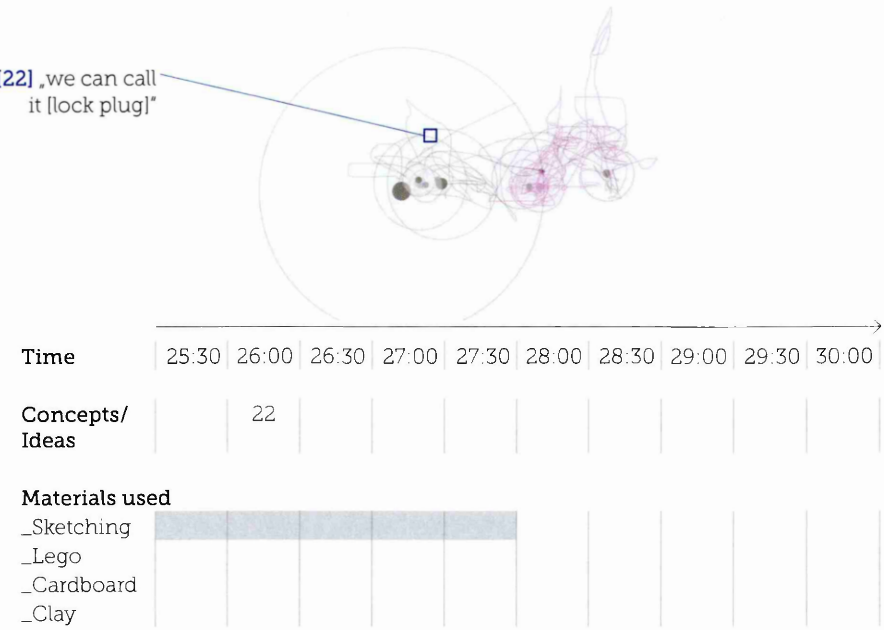


Figure 161: Design moves occurring between minutes 25-30 of experiment 22.

Experiment 22 shows the an intensive use of the interpersonal space. The smaller dots and circles also indicate that pauses were shorter than in the other experiments. What seemed to be lacking, when compared to experiments 16 and 19, was an initial brainstorming phase. Although a few ideas were exchanged, the designers very quickly decided on a route to follow.

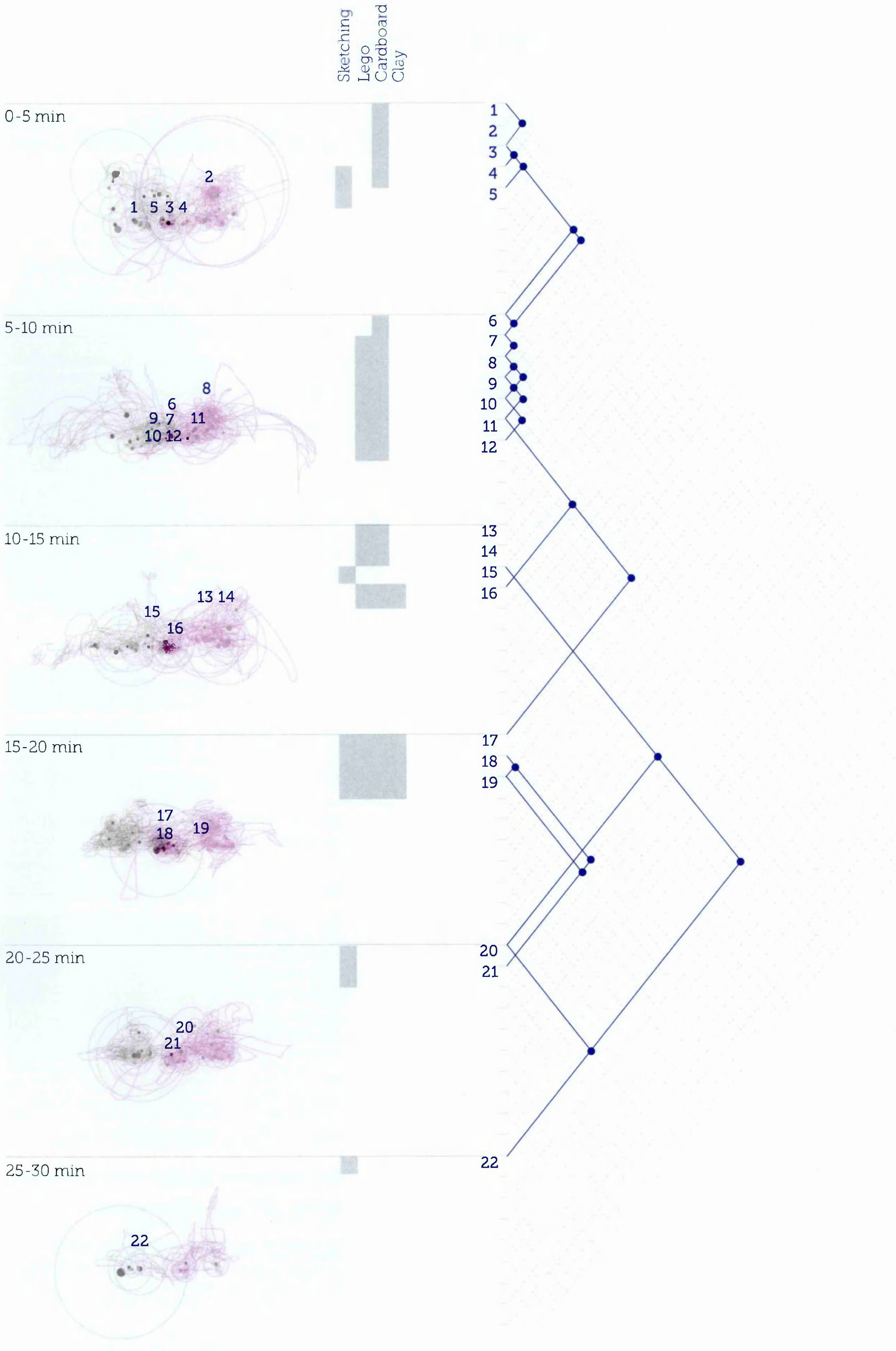


Figure 162: Combined view of Proxemic Motion Trace Analysis and Linkograph in experiment 22.

Linkograph

Taking a closer look at the linkograph of experiment 22, the observations made earlier seem to be echoed. As a striking characteristic of the design process illustrated in Figure 162, the absence of orphan moves can be emphasised. All design moves or ideas recorded seem to be connected to each other in some way. The moves 3 to 12 build a sawtooth pattern (which is slightly distorted by the adapted depiction as a combination of PMTA and linkography). This pattern indicates that quite early on in the design process, starting four minutes into the design task, the participants were thinking in a rather linear manner: one design move leading to another, pushing forward one specific design solution. However, this pattern is broken up in the latter stage of the process.

What appears to be missing is a sequence where the different aspects of a specific design idea would be thoroughly inspected and connected with and evaluated against each other. Such a sequence would be indicated in the linkograph by the emergence of a web pattern.

Design move 15, in which a name for the design solution is being proposed ('watch^2' or 'watch squared') does show the longest link span, reaching to the last design move 22, where the final name is being suggested. Design move 15 was recorded 14 minutes into the design task. The fact, that the participants began to think about a name for their design solution indicates that they already arrived at a mutual understanding and an agreement of what the final product would be in the middle of the design process. This interpretation is somewhat corroborated by the fact that about 11 minutes into the process one participant proposes devising a sketch which would explain their solution – and subsequently, focusing its work on sketching, especially between minutes 20 to 30.

Artefacts produced

The connected nature of the collaboration is reflected in the two artefacts produced by the participants. While agreeing to work on different artefacts after around 11 minutes into the task, the prototype and the sketch showed a very high congruency in the features they display.

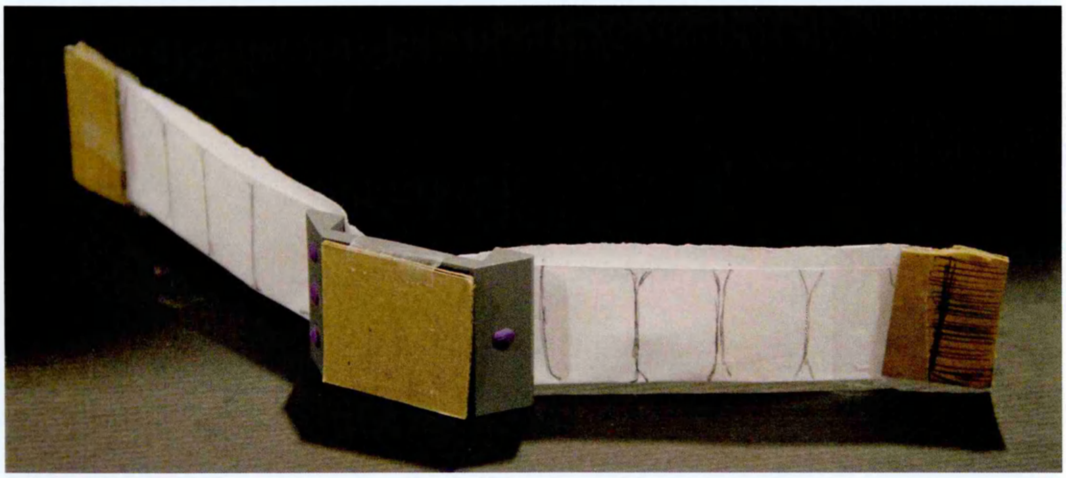


Figure 163: Watch prototype made of cardboard, paper, Lego and clay.

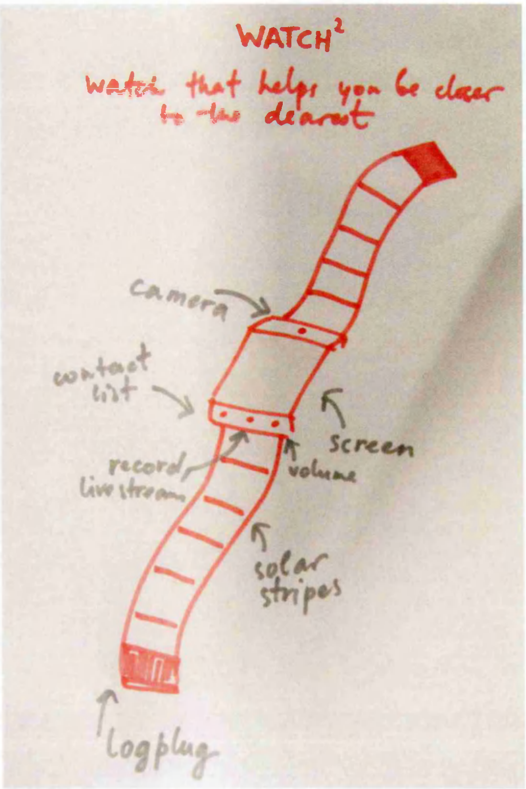


Figure 164: Sketch drawn to illustrate the watch's different features.

Connectedness

Analysing the connectedness of the collaborative design activities, experiment 22 shows another example of a very connected design process (Figure 165). Three times the highest score was reached. The lowest scores were recorded at the median value of 6. Notably, the ratio of contributed design moves dropped in the last segment to the lowest individual score of 1. This might be due to the fact that the participants chose to split up, with one participant drawing an explanatory sketch and the other finishing the prototype. This separation can also be seen in the appropriate PMTAs of the last two segments. The focus of the motion traces gradually moved away from the interpersonal space between the two participants to their individual spaces.

Experiment 22 | *Connected Designing*

Degree of Connectedness per Observational Segment

	0-5 min	5-10 min	10-15 min	15-20 min	20-25 min	25-30 min	30-35 min	35-40 min
Degree of symmetrical motion traces & synchronous motional activity	3	3	3	3	3	2	-	-
Ratio of contributed ideas/design moves	2	1	3	2	3	1	-	-
Degree of linkage between ideas/design moves	3	3	1	3	3	3	-	-
Degree of connectedness	**8**	**7**	**7**	**8**	**8**	**6**	**-**	**-**

(Lowest value: 3, highest value: 9)

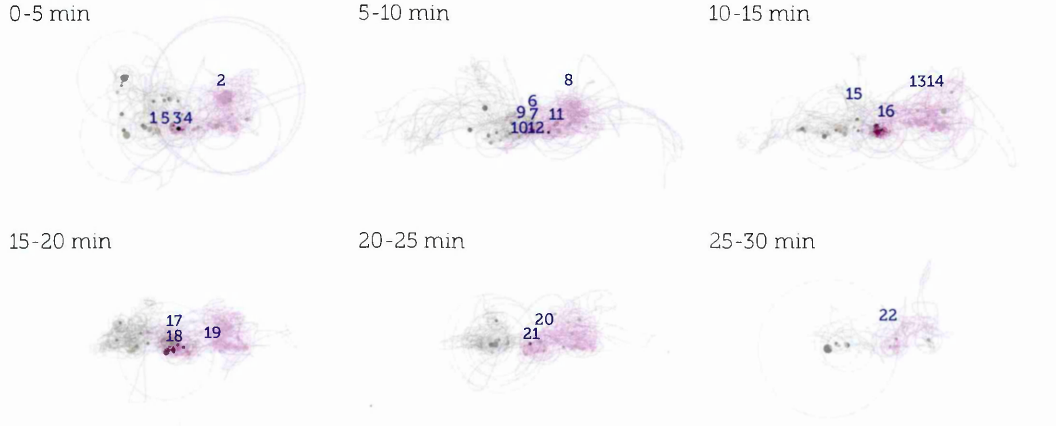


Figure 165: Evaluation matrix for the degree of connectedness and PMTAs of the individual phases of experiment 22.

While the first and the middle segments clearly show a high degree of connectedness, the third and the last two segments differ in the nature of the collaboration occurring in them. In the third segment, the symmetry of the motional activity is equal, but the linkage between the participants' design moves is rather weak, while the ratio of contributed design moves is slightly biased. There is again a drop in the calculated scores at the end of the experiment. In the last segment, only one participant contributes design moves and the symmetry of motional activity tails off. However, the design moves seem to be highly linked to the moves proposed in previous segments.

Summary of experiment 22

In experiment 22, a case of connected designing can be observed. Using all four prototyping media provided, the motional activity was most intense in the first two-thirds of the design process, where three-dimensional prototyping media were used. Once the participants switched to sketching, the activity showed a separated pattern, similar to the sketching activities observed in earlier examples. Notably, the first idea emerged while using cardboard. Subsequently, the discussion moved very quickly into details of the design solution. The linkograph illustrates that no orphan moves were recorded during the whole process, indicating that no brainstorming phase took place, where many possible design directions would be explored. It also shows that, early in the process, the participants seemed to think in a rather linear fashion, following one specific idea. In the middle of the process, verbal expressions indicate that the participants had already a very precise idea of their design solution. They decide to split up the work, one finishing the model, the other drawing a sketch presenting and explaining the design solution. This corroborates earlier observations of sketching being used to express preconceived ideas. Overall, the measured connectedness of the experiment is very high, dropping off a little toward the end, where sketching was used. This also supports the findings made in earlier examples.

In this chapter a closer look was taken at the intensity of movement, rate of talk, gestural types, and verbalised thoughts, as well as the emergence and linkage of concepts to design moves. Investigating the design process, not just in individual analyses, but bringing together different kinds of perspectives in order to gain a more comprehensive understanding of what is going on when we design, offers intriguing insights. Reflecting the role artefacts and prototyping media play in the design process, and particularly in design discussions, such a converging view of the data obtained in 23 controlled experiment appears to be fruitful. The next chapter will discuss and interpret the results obtained in these analyses.

7

7 Interpretation and discussion

Two initial hypotheses underlined the main research question of this thesis as to *how different types of prototyping media contribute to collaborative design processes, particularly the 'quality' of verbal and non-verbal interaction*: (1) different kinds of prototyping media inform qualitative aspects of social dynamics in collaborative design processes; and (2) different kinds of prototyping media inform the co-construction of knowledge in collaborative design processes.

This chapter will interpret and discuss the results obtained in the previous chapter and set them in relation to the hypotheses proposed.

7.1 Interpretation of the skill-building tasks and main design tasks

7.1.1 Materials and social dynamics in collaboration

Overall, the results presented in this thesis indicate that there is evidence to suggest that different materials can inform the quality of social dynamics in collaborative design processes. The prototyping material informs the quality of verbal and non-verbal interactions in several ways:

The rate of talk was found to differ with individual prototyping materials in the way that certain materials informed active collaboration with decreased levels of verbalisation. Comparing the rate of talk occurring in the sketching and the Lego condition – as the two most contrasting activities – the data obtained in the skill-building tasks revealed that, while using Lego, the verbal rate was attenuated during certain phases of the design process as both participants were active in the interpersonal space. Clearly, some sort of collaborative design activity was going on. However, it seems that this form of activity was not amenable to verbalisation. This has been observed previously by Lloyd et al. (1994) and led them to conclude that designing should not be seen as one activity, but instead as "consisting of many interlocking and overlapping processes" (p. 239) which incorporate different modes of thinking. Somewhat in accordance, Clark (2008) puts forward the idea that certain kinds of thinking can only occur when hands are actually moving. Furthermore, this echoes work such as Casakin and Badke-Schaub's (2013) observation that the more mental models become shared, the less verbal communication seems to be needed.

The intensity and location of hand movements were found to differ with individual prototyping materials in the way that certain materials informed a more converged motional activity in the interpersonal space while the other informed a more separated motional activity within the personal spaces. When looking at the intensity of movement occurring in the skill-building tasks, the data showed that when participants employed two-dimensional prototyping, i.e. sketching, the locus of their individual motional activities remained to a large degree within their personal spaces. When using one of the three-dimensional prototyping media provided in the experiments, clay, cardboard and Lego, the interpersonal space between the two participants was used significantly more frequently and more intensely. In addition, more pauses were recorded when sketching compared to using a three-dimensional prototyping medium. These results seem to imply that, when using three-dimensional media, people tend to leave their individual spaces more readily and interact more intensely in the shared space. This might have significant effects on the quality of collaborations and design discussions. As Lawson (2001) points out, the way we use "the language of space" communicates, for example, "our willingness or otherwise to be approached, interrupted, greeted and engaged in social intercourse" (p. 2).

The separateness and connectedness of collaboration were found to differ with individual prototyping materials in the way that certain materials informed more connected forms collaboration. Converging different perspectives in the analysis of seven main design tasks, similar characteristics of the design activities, as observed in the skill-building tasks, could be discerned. In experiment 16 a separated collaboration could be observed, when the participants were using sketching as a prototyping medium. In this instance, the two participants interacted asymmetrically and in a distanced manner, as indicated by the motion trace analysis. Moreover, their ideas and design moves were only loosely connected, further supporting the interpretation as a rather separated collaboration. Experiment 19 illustrates the transformation occurring when participants change the prototyping medium. Starting out sketching, the motional traces remained very much in the personal spaces, but once clay was used, the focus of interaction switched to the interpersonal space. Notably, the design moves became increasingly linked once the material had changed. A similar picture presents itself in experiment 22. The participants started out using all four prototyping media early on, resulting in an intensive use of interpersonal space and linked design moves. Towards the end of the design process, the participants decided to split up with one assigned to draw an explanatory sketch. Once this split was made, the motion traces recorded again showed a separation into the personal spaces. Notably, however, the artefacts produced in this experiment, a physical model and a sketch, still showed a high degree of congruence in their representation of the underlying design concept.

These observations were consistent over the rest of the experiments that were analysed in more depth. Experiment 1 did show the same symmetric and linked collaboration, with the participants using all three three-dimensional prototyping media provided. The same symmetry could be observed in experiment 4, where also all three-dimensional media were used. Notably, in this example, the participants skipped an early divergent search for different design directions in favour of immediately starting to prototype. Experiment 5 depicts the same convergence of activity in the interpersonal space once three-dimensional media are used. Experiment 12, using only sketching, could be characterised as a case of increasing separateness. While the participants agreed upon a shared design direction during brainstorming, they split up after sketching, resulting in an increasing degree of separateness in their collaboration. In this instance significantly more pauses and periods of inactivity, indicated by dots and circles, were recorded. This might, on the one hand, lead to the interpretation that sketching is an activity that requires more pauses to reflect and evaluate the artefact produced. On the other hand, it could be speculated that sketching might inhibit concurrent verbalisation: for example, by consuming more cognitive capacity in externalising a pre-formulated idea than when using three-dimensional prototyping media. The same experiment, however, shows an increase in the overlap of motional activity between minutes 10 to 15 as well as 20 to 25 while using sketching. This observation remains unaccounted for. It could be speculated that both participants were skilled in sketching, which mitigated their reluctance to interfere with each others sketches. Such an interpretation seems to be supported by the quality of sketches produced in this experiment.

7.1.2 Materials and knowledge construction in collaboration

There is strong evidence to suggest that different kinds of prototyping media inform the co-construction of knowledge in collaborative design processes. The immediacy of use and the tentativeness of prototyping materials informs the co-construction of knowledge in collaborative design processes in several ways:

Different kinds prototyping media were found to support preconceived or emergent ideas. When analysing the results gained by observing the use of different gestural types during the design discussions, a difference between the prototyping media became apparent. When sketching, the participants used representational gestures, i.e. gestures that are meant to represent something, at the beginning of the design process. When using three-dimensional prototyping media, the reverse was the case. One way of interpreting this observation might be to infer that, when using sketching, the participants had already formed a preconceived idea or concept in their minds which they proposed in the beginning. On the other hand, it appears that when using three-dimensional prototyping media, ideas emerged from the design activity performed while searching for a design solution.

Delving deeper into the issue of preconceived and emerging ideas, analysing twelve skill-building tasks, the sketching and the cardboard condition yielded similar results. In both cases, most of the ideas were proposed and discussed at the beginning of the tasks, compared to the Lego condition, where ideas were discussed either in the beginning and the end, or throughout the process. This seems intuitive, since sketching as well as using a semi-structured material like cardboard requires a certain degree of advance planning and coordination of the individual activities. Cardboard, as a semi-structured material, for example, needs to be cut into different shapes, glued or stuck together. Similarly, figurative sketches require certain design decisions in advance. With Lego, on the other hand, shapes and forms can be assembled and disassembled quite intuitively without much planning.

Different kinds of prototyping media were found to inform the cognitive influence, which affects the separateness or connectedness of collaboration. In the main design task of experiment 16, sketching was first used after around 6 minutes. Interestingly, it was only used briefly. The actual main sketching activity seemed to start only after 21 minutes. One interpretation of this observation might be that, while in the previous experiment using three-dimensional prototyping media working with the materials sparked new ideas, sketching might be used more as a notation of ideas emerging from the brainstorming phase. The main design task of experiment 16 was also characterised by a loose connection between the individual design moves of the designers, indicating that the participants did not engage in an intense co-construction of knowledge. Related observations could be made in the main design tasks of experiments 19 and 22. Once the prototyping media changed from two-dimensional to three-dimensional the design moves became more connected in experiment 19 and vice versa in experiment 22. Notably, such changes were observed to coincide with a change in the nature of design moves contributed. In experiment 5, for example, while in the brainstorming phase, the design moves proposed were exploring various possible design directions, once a three-dimensional prototyping medium was used, they changed to being very specifically concerned with the individual functional or aesthetic properties of the design solution.

In trying to measure the degree of connectedness occurring in the individual experiments – evaluating the symmetry of interaction, the equality of contribution and the mutuality of cognitive influence – these observations were reflected in the calculated values. Looking at 5-minute segments of the design process, experiment

16 did show an average below the median value, even scoring the minimum value two times. Experiment 19 was evaluated way above average, scoring the maximum value in four out of six segments. Experiment 22 was evaluated almost equally above average regarding the degree of connectedness, yielding four segments showing values between 8 and 9 out of six 5-minute segments analysed. Experiments 1, 4 and 5 ranged above average as well. Notably, the specific combination of the individual evaluations (of the symmetry of interaction, equality of contribution and mutuality of cognitive influence) did seem to be in accordance with the observations made in the previous analyses. In experiment 12, for example, the increase in separateness identified could also be seen in the measured values.

Having set the results in relation to the hypotheses proposed, in the general discussion we will look at their significance in regard to the existing literature.

7.2 General discussion

The discussion of the hypotheses in the previous sections allows to answer the main research question posed in this thesis as to *how different types of prototyping media contribute to collaborative design processes, particularly the 'quality' of verbal and non-verbal interaction*. Different types of prototyping materials have been found to inform social dynamics and knowledge construction in collaborative design processes. The following sections will discuss these findings from a more general perspective related to the existing literature.

7.2.1 Prototyping media and social dynamics

Fluid collaboration

Investigating how designers interact to accomplish fluid collaboration, McDonnell (2012) proposes to look at three axes of attention movement: (1) between the requirements and the design; (2) between design context and use context; and (3) between breadth and depth. This thesis has shed some light on the understanding of how different prototyping media contribute to these movements. When using sketching, for example, the flow between the discussion of requirements and the design solution seemed to be inhibited. Design ideas were found to be predominantly preconceived, discussed and subsequently brought to paper. The discussion of the solution requirements and the design was separated into two steps. This, however, was not the case when using three-dimensional prototyping media. When moving between design context and use context, three-dimensional prototyping media informed the verbal and non-verbal interaction in a different way than sketching. In contrast to sketching, the multi-modal nature of three-dimensional prototypes did allow one to test design ideas in a concrete use context, resulting in new ideas and refinement. The movement between breadth and depth seemed to be mediated by the prototyping medium as well. Three-dimensional media tended to let the participants focus on specific features, primarily functional or aesthetic properties, of a design solution while sketching did less so, indicating that it was more conducive to explore the breadth of design possibilities.

'Fluid' and 'frozen' materials

One way to look at these findings might be found in Whyte et al.'s (2007) distinction between 'fluid' and 'frozen' materials. Whyte et al. define materials as "fluid, when they are altered through the unfolding practice; and frozen, where they are referred to and talked about, but themselves remain unchanged" (p. 21). These categories, however, are not absolute. Materials can unfreeze and refreeze. Based upon the observations made in this research, it could be speculated that when an asymmetrical collaboration occurs – be it, for example, by a difference in skill, expertise or personality – some materials might freeze more readily than others. It has been argued before that sketching requires some degree of artistic skill and often serves to visualise preconceived ideas. Such features might encourage sketching as a prototyping medium to freeze more quickly. An observation supporting this interpretation was made when sketching was used to visually record the ideas brainstormed and to annotate the final design solution in two main design task experiments – illustrating two main activities frozen materials are used for. Whyte et al. (2007) point out that "acts of unfreezing and refreezing visual materials, and the associated representations, are important in structuring social relations for delivery" (p. 21). In this regard, a prototyping medium more prone to freeze when an asymmetrical collaboration manifests itself might impede the occurrence of fluid collaboration as proposed by McDonnell (2012). By guiding the designers' focus on specific, functional or aesthetic properties of the collaborative design solution, and by being more tentative in nature, structured and unstructured prototyping media might be able to resist becoming frozen in such situations, and, thus, to enable a more fluid collaboration.

Focusing nature of prototypes

In comparison to three-dimensional prototyping media, sketching focused conversations less on specific features of a design solution and explored them in less detail. When using three-dimensional prototyping media, the quality of the verbal interaction was characterised by much more specificity. It has been argued that prototypes lead to decreased design fixation (Viswanathan & Linsey, 2009; Youmans, 2011). The results of this thesis might be interpreted as a contradiction to such claims. Ball, Onarheim and Christensen (2010) argue that designers tend to first explore the breadth of possibilities before developing a solution in more depth. However, according to Ball et al., expert designers when facing high-complexity requirements, will especially switch from a breadth-first to a depth-first approach when trying to "assess the viability of uncertain concepts and gain confidence in their potential applicability" (p. 572). The results from this thesis's research, therefore, could also be seen as an indication that using three-dimensional prototyping media facilitates an earlier, necessary focus and tackling of complex design issues in collaborative design processes.

Connectedness

When looking at the data, it showed that sketching resulted consistently in more separated collaborative design activities. When sketching, for example, the locus of the motional activity used to be within the personal spaces of the participants. When using three-dimensional media, the interpersonal space between the two participants was used much more intensely. When using different characteristics of collaboration proposed by Dillenbourg (1999) – being the symmetry of interaction, mutuality of cognitive influence and equality of contribution – to measure the connectedness of the collaborative activity observed, these differences were also echoed in the individual scores. The experiments in which three-dimensional prototyping materials were used did show a higher degree of connectedness than the experiments, where only sketching was used. One way to interpret these findings might lie in Barbapour Chafi's (2014) observation that sketches can only be read in a visual way, while physical models enable the designers to interact with the artefact in more ways than just to look at it. Another interpretation could be that sketching is thought of as something more artistic than working, for example, with Lego. Lawson (2006) suggests that "the form of representation used and the skill in using them are likely to have a huge effect on the design process." This could result in a reluctance, especially from novice designers, to show their work for fear of the drawings not being artistic enough, as well as to interact in each other's sketches. When using three-dimensional prototyping materials, such inhibitions seemed not to occur in the experiments. A possible explanation of this observation could be a more tentative nature of three-dimensional materials.

McDonnell (2009) proposes the conversational strategy of tentativeness as a crucial feature of constructive collaboration. By allowing the proposal of design ideas without signalling commitment and to backtrack on decisions made in an easy way, tentative moves help to resolve disagreements and ensure design progression. Such moves are fostered by using materials like Lego instead of sketches, which make it much harder to propose, alter and backtrack design ideas in a tentative way.

7.2.2 Co-construction of knowledge and prototyping media

Sharedness of mental models

The differences observed above relating to the degree of connectedness could also be seen as giving clues to the sharedness of mental models in collaborative design processes. Casakin and Badke-Schaub (2013) argue that a higher degree of sharedness leads to a decrease in the verbal rate, as designers do not need to discuss anymore to reach a shared understanding of each other's ideas. Indeed, such a decrease in the verbal rate could be observed in the experiments when both participants were working in the shared space between them when using Lego. Dong et al. (2013) point to the importance of team cognition in the performance of multidisciplinary teamwork. They argue that team mental models support coordinated team performance. In this context, the results of this thesis indicate that more connected collaborative design activities, occurring when three-dimensional prototyping media were used, lead to more shared mental models, and indeed better team performance.

Emergence of concepts

When analysing the emergence of ideas and concepts in the experiments, the participants did seem to express preconceived ideas when sketching, and to let concepts emerge while working with prototypes. This might be linked to two observations made by Perry and Sanderson (1998) and Edelman and Currano (2011). Perry and Sanderson (1998) report that prototypes not only serve as a resource for discussion, but also are formed and generated by them – arguably leading to new insights and concepts in the process. Why this is not happening to the same degree when using sketching might be found in the material itself. Edelman and Currano (2011) propose that 'ambiguous media' lead to divergent discussions and 'mathematised media' to convergent discussions. While sketching could be characterised in many ways as ambiguous, in contrast to clay, for example, it requires much more thought and reflection before drawing an idea, especially in the context of design discussions. When using clay, on the other hand, a designer can start forming shapes without having a preconceived idea. Eckert et al. (2013) propose that the implicit and explicit formality of design processes, interactions and representations creates and restricts the possibilities of how designers plan and execute their collaborative activities. A sketch could be argued to possess a higher degree of formality, by its requirement for the preconception of ideas and artistic skill, than three-dimensional prototyping. Such a difference could account for why concepts emerged from the collaborative design activities when using Lego or clay, but much less so when sketching.

Facilitation of joint knowledge transformation

This observation also relates to the concept of prototypes as boundary objects. Carlile (2002) proposes that boundary objects provide a shared language representing the individual participants' knowledge, a means to learn about the differences, and a means to facilitate the collaborative transformation of knowledge. Particularly when using three-dimensional prototyping media, these characteristics could be observed. When using Lego, for example, everyone seemed to be equally skilled and knowledgeable of how to use the bricks and elements, resulting in highly shared artefacts and a connected collaboration. When sketching, the proficiency of drawing and reading two-dimensional representations of design ideas – or lack thereof – seemed to significantly restrict the sharedness of the artefacts. In addition, the emergence of ideas and concepts during the design process using three-dimensional prototyping media supports Carlile's (2002) as well as Holzer's (2012) claims that prototypes facilitate joint transformation of knowledge. It could be speculated that the higher degree of sharedness in three-dimensional prototyping could result in a stronger sense of ownership in the design solution. McDonnell (2009) argues that collaborative negotiation fosters the designers' notion to take ownership of a design concept, which results in more effective collaboration. The more the artefacts are shared – as when using Lego – it could be proposed, the more the participants take ownership of the collaboratively constructed design solution.

In this thesis, no attempt was made to evaluate the value, quality or creativity of the design solutions developed during the individual experiments. Thus, it does not try to make any inference on the relation between the prototyping media used and the quality of the solution. In addition, the thesis did not attempt to evaluate sketching as a design method. Over the centuries, drawing has proved itself an indispensable tool not only for designers, architects and engineers, but also for almost all creative professions. Thus, this research has to be understood as far from diminishing the inherent and indisputable value of sketching. However, it tries to shed light on the relation of the various prototyping media at the disposal of the designer and the interactions occurring when using them. Brereton et al. (1996) have identified quite a while ago that "many solution proposals and interpretations of requirements clearly arise from designers' interacting with available hardware" and proposed that a "compelling analysis would result from examining how hardware acts as a negotiator to steer the activity" (p. 339). This thesis has tried to provide such an analysis.

8

8 Conclusions, limitations and implications

8.1 Conclusions

Prototypes not only epitomise what design appears to be in the general perception, they really are a crucial and essential aspect of every designer's work – albeit that, the shiny object unveiled from a black cloth to a stunned public is only the tip of the iceberg. In practice, often simple and crude prototypes made out of paper, cardboard, foam, clay or whatever material seems to fit the purpose are being used to help the designer's cognition. Thus, prototyping is an integral and fundamental part of every design process – even more so as, in today's professional world, the necessity for designers to collaborate appears to be constantly increasing. While it might be argued that, when developing solutions for complex problems, they always needed to work with other designers and professions, it could be argued that this has become a conditio sine qua non in the light of the ever more converged products we use today – from smart phones, to smart watches, and – why not? – smart fridges, to name only a few. In practice, design collaboration in the form of design discussions most often occurs over design artefacts. Thus, it seems appropriate to look at these two essential parts of the design process – prototyping and collaboration – more closely. However, the role of such artefacts in collaborative design processes and the qualities of the collaborative design activities they enable are still an under-researched area. This might be due to the difficulty of measuring the verbal and non-verbal components of collaborative design activities that occur when prototyping.

This thesis set out to investigate how different types of prototyping contribute to collaborative design processes, and the verbal and non-verbal interaction occurring within them in particular. By moving from unstructured field observations to controlled experiments, it has shown that three-dimensional prototyping, in contrast to two-dimensional prototyping, resulted in more connected types of collaboration, fostered the emergence of design ideas throughout the design process, focused discussions on aesthetic or functional aspects depending on the materials used, and led the designers to pay more attention to specific features of a design solution.

The investigation conducted in the course of this thesis evolved from observed practice to observable practices. First, a look into the context of everyday design activities was taken. *How do designers work? How do they collaborate? What prototypes do they use? How do they organise their workspace? When and where do they talk about their designs?* Questions like these guided the first inquiry conducted in the form of unstructured field studies. For this purpose, an industrial design, a graphic design, an experience design, and an interaction design studio were analysed in more depth. To contrast these insights with practices outside the design world – which could also be described as creative, albeit not in a traditional understanding – the thesis also looked at a research group at Princeton University. The observations made echoed the importance of prototypes in the design process, as suggested in the literature. Various kinds of prototypes found in the existing literature, could be identified in design practice. For example, prototypes found were used as 'proof-of-concept' and 'proof-of-production' prototypes, according to Ullman's (2003) classification. They were also observed to possess the three dimensions proposed by Houde and Hill (1997) – 'role', 'function' and 'form' – although in design practice prototypes were observed to be designated representing a 'function prototype' or a 'style prototype'. In addition, another quite significant type of prototype found was 'throwaway' (Sommerville, 1995) or 'experimental' (Budde et al., 1992) prototypes. All the expert designers interviewed emphasised the importance of working with the artefacts, pointing to the 'power of the real' which prototypes seem to possess. Furthermore, in observing designers at the interaction design studio using data from a live webcam video feed, the importance of discussions in the design process became apparent: the designers spent more than one-third of their time discussing. While not being able to actually hear what they were talking about, it can be assumed that some sort of verbalised negotiation or construction of the design solution took place as suggested by Bucciarelli (1994), Lloyd and Busby (2001) and Ariff et al. (2013).

These first observations pointed to the roles artefacts may play in the design discussions, for example, by focusing the conversation on specific aspects and contents of a design solution. Glock (2009), however, suggests that such discussions are not only limited to verbalised communication, but also extend into non-verbal interaction, and are characterised by a "simultaneous use of different kinds of semiotic practices in different media (such as language, gesture, and drawing) which mutually elaborate each other" (p. 5). Therefore, these findings raised more questions, such as: *How exactly do prototypes relate to the discussions they are used in? Do specific kinds of materials have different effects on the verbal and non-verbal interaction between designers? And: how do two-dimensional prototyping media, like sketching, differ from three-dimensional materials?*

In order to answer these more focused questions, it became apparent that a more controlled approach was needed. Design research, as an integrative discipline, draws upon methods from many scientific domains, as Friedman (2003) points out. Cross (1999) emphasises that design researchers need to use those traditions of scientific inquiry while developing their "own intellectual culture, acceptable and defensible in the world on its own terms" (p. 7). The methods used most frequently are expert interviews, observations, case studies, protocol studies, reflection and theorising, as well as simulation trials (Cross, 2006), all of which have their own advantages and disadvantages. Interviews, observations and case studies have been useful in the earlier part of this thesis, as they allowed to discern 'real-world behaviour' in design practice. However, they fell short when trying to obtain and analyse the data in a more controlled way. Cross (2006), for example, points out that interviews have been used predominantly to obtain the designers' thoughts about their processes and procedures in an unstructured way. Case studies receive a harsher critique, such as Campbell and Stanley (1966) who argue that "such studies have such a total absence of control as to be of almost no scientific value" (p. 6). These limitations were also experienced, to a certain degree, in the course of this thesis. Interviews, observations and case studies served well to identify potential categories early on, but seemed unable to provide sufficient depth and control in later analyses.

To investigate the role of prototypes in collaborative design processes, especially in regard to verbal and non-verbal interactions, in a more controlled experimental context, a new method was developed for this thesis in a series of pilot studies. Different group sizes, materials, forms of presentation and recording, as well as analyses, were tried before moving to the main study with a refined and tested experimental set-up. Gradually, a more visual approach to analyse the data recommended itself from the insights generated. This development led to the formulation of a new methodology for analysing design activity, the Proxemic Motion Trace Analysis (PMTA). This new approach of investigating design activity represents one of the two major contributions of this thesis. By converging various aspects of the design process, which have formerly been looked at only individually, the methodology allows for a more comprehensive understanding of what is going on when designers collaborate. It also provides an enhancement for other methods of analysis, like, for example, Goldschmidt's (2014) linkography. As a way to visually notate and link individual design moves of a design process, linkography enables the identification of critical design moves and patterns of design activity. However, through its abstract matrix representation of the design moves, it separates important aspects of the design process from its analysis. Used in combination, the PMTA allows linkographic analyses to incorporate critical characteristics, like the individual designers' spatial activities performed, the symmetry of interactions occurring, or the location of the origin of the design moves – providing a much more integrated picture of the collaborative design process. These more holistic insights into the design process, however, could also be used in combination with more focused methods, like conversation analysis to set the verbalisations analysed into a wider context.

The main study gathered and analysed the data from 23 controlled experiments. Participants were recruited amongst the students of the University of the Arts

London's Central Saint Martins College of Arts and Design. In each experiment, two design students were paired up to work collaboratively on different tasks. A skill-building task was given to familiarise the participants with the materials provided as well as to focus on individual differences of designing with these materials, and a main task to simulate a real-world project brief. An unstructured material, clay, a semi-structured material, cardboard, and a structured material, Lego, were provided as three-dimensional prototyping media. As a control condition, a two-dimensional prototyping medium – a sketch pad and pencils – was handed out.

By analysing selected aspects of the design activity observed – like verbal rate, intensity of movement, gestural types or the emergence and linkage of ideas – various characteristics could be discerned of the relation between prototypes and the quality of the discussions occurring during the experiments. The most striking finding was the apparent difference between the three-dimensional prototyping media, clay, cardboard and Lego, and the two-dimensional medium, sketching. An effect of the prototyping material of a design artefact on the design process was suggested earlier (Lawson, 2006; Whyte et al., 2007; Leifer & Steinert, 2011). Leifer and Steinert (2011), for example, argued that "the choice of prototyping material or environment directly influences the amount and degree of generated alternatives" (p. 397). An influence of the different prototyping materials on design processes could certainly be observed in the experiments.

8.2 Claim to new knowledge

This thesis contributes to the existing knowledge in two ways:

(1) By providing a new methodology, the Proxemic Motion Trace Analysis PMTA, to analyse collaborative design processes in a more integrated way and to enhance existing methods; and

(2) By contributing new findings to the understanding of the role of prototypes and the media used to produce them in collaborative design processes, especially in regard to the verbal and non-verbal interactions.

8.2.1 PMTA methodology

The Proxemic Motion Trace Analysis PMTA allows design researchers to converge different aspects of collaborative design activities in order to gain a more comprehensive understanding of design processes. On the one hand, the PMTA provides a new opportunity to obtain and analyse valuable data on how designers use the personal and interpersonal space when collaboration is co-located. This appears to be an important aspect of any collaborative design activity, as the way people use space to – often subconsciously – communicate with others reveals crucial information about how they feel and think about the other, the design solution developed, and the collaboration taking place. On the other hand, PMTA can be combined with established and valuable research methods, such as protocol analysis, observation or linkography, in order to gain a fully integrated picture of design processes. The results obtained in the course of this thesis suggest the conclusion that the method developed in the course of this thesis can indeed provide a more comprehensive picture of the verbal and non-verbal interactions occurring in collaborative design processes when using different types of prototypes. By incorporating different perspectives on design activities, it allows researchers not only to rely on one specific analysis, but to combine different aspects in order to reflect on the data in a more cross-linked way.

The significance for design research is to be found in the more integrated perspective and understanding of different individual aspects of designerly ways of solving problems, offered by the Proxemic Motion Trace Analysis. The findings are also significant in regard to future research, investigating the role of prototypes in design collaboration.

8.2.2 Prototyping media and design collaboration

The research reported in this thesis indicates that there is strong evidence to suggest that, when building prototypes, differences in the artefact's prototyping material result in variances in the quality of verbal and non-verbal interaction occurring on and around them. Thus, this thesis also contributes to the existing knowledge by bridging the gap of knowledge at the intersection between prototypes and co-located design collaboration. Despite their importance in today's collaborative design processes, particularly the interrelations between the artefacts used, their prototyping material, and the verbal and non-verbal interactions they enable, they still represent an under-researched area. This thesis provides important insights into how different prototyping media inform such collaborative design processes.

Particularly when comparing two-dimensional and three-dimensional prototyping media, the quality of those interactions and, more generally, the collaborative design activity, differed. Sketching, as a two-dimensional prototyping medium, resulted in more separated, individualistic types of activity, with the designers often splitting up their work and mostly remaining within their personal spaces. When using three-dimensional prototyping media, the participants used the shared, interpersonal space between them significantly more intensively, and showed more connected types of collaborative design activity. According to the research conducted in this thesis, the quality of the verbal and non-verbal interaction showed a tendency towards being connected, emergent, specific, and focused when using a structured three-dimensional prototyping medium. This was the case, too, when using an unstructured prototyping medium, although its focus differed in its subject, emphasising the aesthetic properties of the artefact instead of its functional features. In contrast, when using the two-dimensional medium of sketching – and, to a certain degree, the semi-structured prototyping material – the quality of interactions was much more separated and prescriptive, but less specific and focused. Overall, these results of the thesis offers design practice valuable insight into how collaborative design activities can be planned, managed, informed and supported using specific prototyping media in order to achieve improved processes.

8.2.3 Main conclusions

The main conclusions of this thesis are as follows:

(1) *Integrated analysis of collaborative design processes:* The research reported in this thesis provides evidence to support the validity and reliability of the proposed, new research method Proxemic Motion Trace Analysis PMTA to investigate collaborative design processes. The new method offers an integrated perspective of collaborative design activities and allows researchers to analyse them in a combined and cross-linked way.

(2) *Prototyping materials and social dynamics:* The results from 23 experiments reported in this thesis indicate strong evidence to suggest that the kind of prototyping media used informed qualitative aspects of the social interaction. As one qualitative dimension of artefact-facilitated design conversations, the connectedness of collaborative design activities was investigated in more detail. The data obtained and analysed can be interpreted as to reflect a difference in the way three-dimensional prototyping media and the two-dimensional control condition, sketching, facilitated connected design activity. Three-dimensional prototyping media were found to stimulate a higher degree of connectedness than sketching. In addition, the analysis of 99 individual design tasks showed repeating patterns in the proxemic behaviour facilitated by the three-dimensional prototyping media provided and the control condition sketching. Three-dimensional prototyping media were found tending to support a higher intensity of motional activity

overall as well as a more intensive use of the shared, interpersonal space between the participants. These findings indicate new insight into the role different kinds of prototyping media might possess in regard to proxemic behaviour understood as a kind of embodied language in the use of space and an important factor in governing the social dynamics of interaction in collaborative design processes.

(3) *Prototyping materials and co-construction of knowledge:* The data analysed in this research produced evidence to suggest that different kinds of prototyping media inform the co-construction of knowledge in collaborative design processes in distinguishable ways. Particularly the immediacy of use (i.e. the ease of use with which materials can be used for designing) and tentativeness (i.e. the degree to which a material communicates the temporality or provisionality of a design) are suggested to inform joint knowledge transformation. Non-structured and structured materials with a high degree of immediacy and tentativeness (clay and Lego) were found to show an inclination to facilitate the emergence of mutually shared knowledge about design solutions from the collaboration itself more, than the semi-structured material (cardboard) and the control condition sketching.

8.3 Scope and limitations of the research

The thesis's goal is to shed light on the interrelations between prototyping and design discussions in order to better understand collaborative design processes. The research tries to tie in different perspectives of investigating design activities, aiming at a more comprehensive view of what happens when people design. It particularly focuses on the role different kinds of prototypes and prototyping materials play in design discussions.

The research presented here has provided insight into the role of prototyping in design collaboration and developed a methodology to investigate their interrelation. The research has been conducted with diligence, good faith and scientific scrutiny. However, it is necessary to point out the limitations of this thesis.

Materials and design phase

Limited by the time frame of a PhD programme, the thesis cannot offer a concluding inquiry into the subject or a comprehensive comparison of all prototyping methods and materials currently used. Its controlled experiments focused mostly on the ideation and early design phase. Thus, the thesis cannot infer much about latter phases of the design process, although observations made in the practice studies, especially in regard to the role of proof-of-production prototypes, suggest that the results might be of relevance in latter stages as well.

Applicability outside the design discipline

Due to the limited time available, the investigation also limits itself to the observation of design activities performed by designers. The main focus is on obtaining and analysing in-depth data from the observations made in design practice and the series of controlled experiments conducted at Central Saint Martins College. A look into how prototypes and discussion – and, in a more general sense, designerly ways of thinking – are employed in domains not related to the design discipline would certainly be of interest. This research, however, tried to gain new insights within the realm of design, which eventually might find their way into other fields of expertise. Since the controlled experiments could investigate the role of prototypes in verbal and non-verbal interactions only amongst student designers in more detail, further research might reveal how expert designers with a higher level of expertise use verbal and non-verbal behaviour with prototypes.

Accuracy of motional activity recording

Another limitation of this research is the mode of recording the motional activity. The activity had to be recorded manually, using publicly available software. Recent work is starting to develop an automated method to record the motional activity of collaborating designers. At the time of this publication, the technology is not ready yet to generate the motion traces according the rules defined in the PMTA. It seems, however, that it is not far from being able to do so. This would mean not only a more efficient process of analysing the video-recorded design activity, but also a more precise method of visual analysis. The manual mode of recording the individual motion traces, used in this thesis, only allows for a certain degree of accuracy and thus interpretability. Using a more precise and accurate mode of recording and visualising the design activity would allow for an even more detailed analysis of the PMTAs.

Reliability of coding & coding rules

There are limitations in regard to the reliability of the coding too. The data in this thesis has been coded by only one researcher. If resources permitted, at least two researchers would have analysed the data and their inter-coder reliability would have been tested. Such an approach is recommended for further investigations using PMTA.

In its present form, PMTA only offers vague coding rules for the proposed measures of connectedness, relying to a large extent on intuitive coding of the data. For example, when assessing the degree of symmetry represented in the participants' motion traces, the coefficients ranging from 1 to 3 – and 3 to 9 for the total scores respectively – are assigned to a certain degree based upon the subjective perception of the researcher. A coefficient of 1 would indicate a visibly low degree of symmetry of the motion traces, while a coefficient of 3 is given to images showing a high degree of symmetry. Only in their pronounced manifestations, the different patterns become clearly distinctive. When assigning the coefficient of 2, the interpretation of the images analysed are much less objective. The main aim of this thesis was to develop a method to investigate design processes in an integrative way. The measurements used to identify the degree of connectedness of the design activities occurring, are proposed as an example of how the data provided by PMTA could be analysed in more depth. As such, the coding of the individual categories of connectedness suggested in this thesis, does not represent an elaborate method of analysis in itself, but requires more refinement for potential use in further research.

Combined measurement of connectedness

The categories used for the combined measurement of connectedness were derived from much referred work done by Dillenbourg (1999). In particular, the symmetry of interactions, the negotiability and synchronicity of communication as well as the influence of cognitive processes have been chosen to serve as measurements of connectedness in collaborative processes. In their combined view, these aspects of collaboration allow to identify to what degree the participants contributed in equal measures to the process, provided their ideas uninhibited to the design solution and have connected to and developed on each others thoughts. In their sum the combination of measures gives an account of how symmetric, shared and intertwined the collaborative design activities observed were.

However, this combination of categories was only proposed to represent one possible way of using data from PMTA to measure a distinct quality of collaborative design processes. This thesis argues for the validity of this approach, but it does come with its limitations:

(1) The symmetry of interactions has been measured by analysing the individual participant's intensity and location of motional activity. Observing their proxemic behaviour the analysis inferred whether or not both participants were working within their personal spaces or the shared space between them and whether they engaged bodily, for example by using gestures, in equal measures in the conversations. While this behaviour was found to be relatively consistent in the experiments conducted in this research, it can be subject to potentially distorting influences, such as injuries or handicaps, individual temper or the experimental set-up itself. Such influences have not been measured in this research.

(2) The negotiability and synchronicity of the communication was measured by recording the number, time and location of the verbalised design moves. This allowed to identify how much each of the participants were contributing in each segment of the design process. While this measurement provided a way to analyse to what degree both of the participants shared their ideas or were inhibited to do so, it did not measure factors that could influence their occurrence as well. Such influences could be that, caused by a perceived difference in personal status, a participant would choose only to contribute design moves conforming with the other participant's view, and thus not bringing in his or her own thoughts into the

collaboration. Such an influences have not been measured in this thesis. However, an in-depth analysis of the verbal expressions in each segment of the experiments could reveal such factors.

(3) The mutual influence of cognitive influence was measured by identifying to what degree the individual design moves have been linked to each other using adapted linkography. This indicator allowed to analyse to what degree the design moves and ideas of each participant were taken up by each other and developed further. However, in this research only the linkage was analysed and not the particular way the link was accomplished. It could be, for example, that one participant would take up the other's idea only ostensibly to promote his or her own concept. A more focused analysis of the conversations could identify such an interaction.

Handedness

It has been argued above that personal traits of the participants not measured in this research, like mood, motivation and physical limitations, can influence the data obtained by PMTA. In the sketching condition in particular, a potentially important factor could be the handedness of the participants. In the experiments all participants were seated either on the left or right side of the working mat in front of the material boxes. This was done without formally assessing the handedness of the participants. However, judging from analysing the experiments' video footage, i.e. the use of pens and tools by the participants, out of 46 participants 7 seemed to be left-handed and 39 right-handed.

The paper provided for the sketching was a standard A4 non-lined writing pad. It is a distinct possibility that the handedness of the individual participants could have an impact in accessing the relatively small pad from either the left or right side. For example, it might be that a left-handed participant would feel more reluctant to use the pad when seated on the left side of the working mat than when seated to right, as it could seem a more space occupying gesture when using the hand further away from the paper. Such a behaviour could be considered as an intimidating act or an indicator of taking over the control, and as such be avoided by the participants.

The A4 format of the paper provided might be another limiting aspect in this regard. As is represents a relatively small area for collaborative work, the results of this research may be an artefact of the experiment. An intriguing question would be whether or not the data would be different when using, for example, a A3 or A2 sheet of paper. It could be argued that a larger format would invite collaboration on the artefact itself more than when providing the small format. However, A4 represents a standard format to which all participants are used to. Even more so, as they all were design students who sketch regularly, probably every day, and use sketches to communicate and discuss their ideas with tutors and other students. Therefore, it would seem that the format would have less of an impact on those particular participants than on people with a background less used to sketching.

Location of resource boxes

The materials or resource boxes have been placed in front of the participants in order to provide an overview of the different materials, to give easy access to each of the boxes and to be able to video-record their use. Due to the dimensions of the boxes, they had to be set in a row next to each other. This implied, on the one hand, that individual boxes could somewhat communicate a sequential order, and on the other hand, that some boxes were closer and others farther away from the individual participants. In the experiments, such an implied sequential order could in some cases be observed. In particular when beginning with the skill-building tasks, the participants would confer with each other where to start. In some instances the western reading direction from left to right seemed to inform the participants' starting point. Therefore, the research chose not to analyse the order in which the materials were used. The distances of the individual boxes had a more direct impact on their use. When using Lego, this observation was most pronounced. Due to the small dimensions of the Lego elements, this box was used the most by far. Searching and grabbing individual pieces generated a high intensity of motional activity to and from the Lego box. In most cases, the participant closer to this specific box would use it more than the other participant, as it was placed on the edges of the row of boxes. This limitation of the data was considered in the analysis.

8.4 Implications

The implications of the research conducted in the course of this PhD thesis may be located in different areas of expertise. Most notably, they contribute to the fields of design research, design practice and design education. However, the thesis's findings can also have implications for other domains where designerly ways of thinking are applied in solving problems, such as innovation management.

Implications for design research, design practice & design education

The primary fields where this thesis's implications seem relevant are certainly to be found in design research and design practice. The scientific interest in designerly ways of knowing, which originates in the design methods movement of the 1960s (Cross, 2001), particularly forms the context of this thesis. In recent years, the discourse on this topic has expanded well beyond the field of design research, leading to a diluted concept of design thinking (Cross, 2010). This development has not been without critique amongst design researchers (Cross, 2010; Nussbaum, 2011; Hassi & Laasko, 2011; Carlgren, 2013). Thus, they have been called to reclaim "design thinking as a fundamental aspect of the discipline of design" (Cross, 2010, p. 99). Such a definition of designerly ways of thinking depends largely on the understanding of the different kinds of activities observable in design processes. This thesis has argued that two prominent perspectives investigate the subject from a prototyping-centred and a social-activity-focused vantage point. In regard to the interrelations between these two aspects of designing, the research conducted has implications within this field of interest, as it allows one to paint a more comprehensive picture of what happens when designers collaborate. It provides a new methodology to jointly investigate prototyping and social activities. This inspires new inquiries, and poses new questions about the designerly thought-processes underlying these processes.

The role of sketching in social activities and collaborative design processes has been looked at in the past (Goldschmidt, 1991; van der Lugt, 2005; Ariff et al., 2010). Such studies have mostly focused on the relations between sketching and verbalisation. This thesis has looked beyond that and shown that different prototyping media influence the social activity, and use of space, as well as verbal and non-verbal interaction. Collaborative design activities have been extensively studied. The method developed in the course of this thesis, however, provides a new perspective on proxemic behaviour and non-verbal interaction, allowing design researchers to gain a more holistic understanding of the design process that does not have to rely on analysing verbalisation exclusively.

In the field of participative design, these findings also seem relevant. When collaborating with different stakeholders, the role of the artefacts used in the sense of boundary objects becomes a crucial factor in conducting successful collaborative design processes. This thesis focused on the collaboration between designers, although the observations made in the pilot studies, where participants from various disciplines (such as psychology, management, journalism and architecture) collaborated, suggest that the findings apply in such contexts, too.

Representing first steps to close gap in the existing knowledge regarding the interrelations between prototypes and collaborative design processes, these findings may also have implications for design practice. Intuitively, designers seem to be mindful about the importance and application of prototypes in their everyday practice. This research, for example, has shown that they choose carefully which type of prototype to discuss with clients in what phase of the process. The findings reported in this thesis might help designers to better understand how the artefacts they use – when presenting or collaboratively working on them – inform the kind of interaction and design activities taking place when doing so.

In design education, this thesis's findings might help design educators to better convey the various roles prototypes, and the materials used in their production, play in design processes. They could, for example, consciously set specific tasks with different prototyping media in a studio setting, in order to let the students experience the influence of the prototyping materials on their design activities. Furthermore, such tasks given to groups of design students, or even mixed groups with students of other disciplines, could provide new learning opportunities of how prototypes and prototyping materials foster or inhibit collaboration.

Implications for innovation management

In the past years, design thinking has become a prominent methodology outside the traditional design world. Particularly when developing radical innovations, it has been heralded by many as a preferred means to that end. By refocusing on designerly ways of solving problems specific to designers, this thesis has gained new insights, which might be transferred again into the management discourse on design thinking.

The ability to develop innovations successfully is largely acknowledged as a major competitive characteristic of businesses today (Tushman & O'Reilly, 1996; O'Connor, 2008; Crossan & Apaydin, 2010; Govindarajan & Trimble, 2010). The origin of innovation research can be traced back to the early 1900s, when Joseph Schumpeter first published 'The Theory of Economic Development' (1934). Like Schumpeter, many distinguish between inventions, which represent the first occurrence of an idea and innovations, which are seen as the widespread distribution of an idea, goods or service (Mascitelli, 2000; Fagerberg, 2005; Tidd et al., 2005; Le Masson et al., 2006; Cruickshank, 2010; Carlgren, 2013). Another way to grasp innovation is to differentiate between degrees of novelty, i.e. between incremental innovation and radical innovation (Robertson, 1967; Tushman & Romanelli, 1985; Lynn et al., 1996; Cole, 2002; Steiber and Alänge, 2013; Norman & Verganti, 2014). Experts argue for the increasing importance of the latter (Tushman & Nadler, 1986; Christensen, 1997; McDermott and O'Connor, 2002; Von Hippel, 2005; Utterback et al., 2006; Suri, 2008). However, in developing radical innovations managers face higher risks, since there is no proven way of development (Von Hippel et al., 1999; O'Connor, 2008; Suri, 2008; Wylant, 2008). Thus, most organisations have organised their development processes since the late 1980s using stage-gate systems (Cooper, 1988) in order to ensure efficient product development by reducing uncertainties (Wheelwright and Clark, 1992). Developing radical innovation, however, requires different processes, methods, and capabilities than pursuing incremental innovation (McDermott and O'Connor, 2002).

Within the management discourse the search for such new approaches has led in the past decade to an emerging interest in the design discipline (Gemser & Leenders, 2001; Bruce & Bessant, 2002; Verganti, 2011; Filipetti, 2011; Verganti and Öberg, 2013; Norman & Verganti, 2014). The reasons given as to why design is considered to possess the potential to contribute to innovation management are diverse. Some argue that it uses a different kind of logic, dealing with complex and ambiguous matters (Bruce & Bessant, 2002; Borja de Mozota, 2006). Others hold that it employs a human-centred perspective and applies a wider approach to solving problems (von Stamm, 2004; Brown, 2009; Hobday et al. 2012; Cruickshank & Evans, 2012). It is commonly agreed that the development of radical innovation is characterised by a high degree of uncertainty (Mascitelli, 2000; Rice et al., 2001; McDermott & O'Connor, 2002). Such vaguely defined situations have also been coined as 'wicked problems' (Buchanan, 1992; Rittel & Webber, 1973), which design thinking is argued to be well suited to solve (Cross, 2006). As a consequence, designerly ways of solving problems have been proposed as a preferred approach to developing radical or breakthrough innovation (Mascitelli, 2000; von Stamm, 2004; Utterback et al., 2006; Dunne & Martin, 2006; Brown, 2009; Filippetti, 2011).

This thesis's findings seem to have implications for improving design thinking practice in management and interdisciplinary innovation projects. By deliberately defining what prototyping medium to use in which phase or to meet which challenge, such collaborative design processes can be made more successful. As shown in the observations in design practice, professional designers often are contemplating such issues already. This is much less the case in the management-related design thinking practice. In contrast to designers, managers are not trained in bringing new ideas on an empty sheet of paper. Thus, externalising their thoughts in a non-verbal way is a much harder task for them. Transforming mental models and concepts into a physical form, however, makes them much more negotiable, and fosters the sense of shared ownership. Using Lego or similarly structured prototyping media, for example, design processes in a management context could make ideas more tangible and make much more use of the emergence of concepts through collaboration, instead of just discussing the ideas put forward in a verbal brainstorming session. In addition, the choice of prototyping media could focus discussions, for example on the functionalities of a solution when using Lego. Switching between different prototyping media, different types of design activities could be evoked, for example by using individual sketching tasks in between phases of collaborative work on three-dimensional prototypes, to allow for individual reflection on the group's design solution.

8.5 Future research

This thesis leaves ample opportunity for future research. The further the investigation led, the more questions and possibilities emerged. There is still a long way to go in order to gain a coherent body of research on the relations between artefacts and collaboration. This thesis is merely able to contribute a small rock to the mountain of work that is still needed. However, a few immediate paths to follow up this specific research may be outlined:

1) Applying the methodology to investigate collaborative design activities of experienced or expert designers. The research done in the controlled experiments using the PMTA only focused on senior design students. Even amongst student designers Cross, Christiaans and Dorst (1992), as well as Atman, Chimka, Bursic and Nachtmann (1999), observed differences between junior and senior students. According to their research, junior design students often lost themselves and got stuck in gathering all available information, while the more senior students filtered out information and immediately processed the data. Expertise seems to play an important role in the way designers solve problems. Cross and Clayburn Cross (1998), for example, argue that experienced designers deliberately treat a problem as ill-defined and thus as a harder problem to solve, as novice designers do. Expertise in any field of profession seems only to be attained after around 15'000 hours or 10 years of deliberate practice and hard work (Ericsson, Krampe & Tesch-

Römer, 1993). Within the field of design practice, differences in the approach of novice and expert designers can be observed. Kavakli and Gero (2002), for example, observed that an expert architect showed twice the amount of design moves and simultaneous cognitive actions to a novice architect. Such observations raise the question as to if and how these differences exert an influence on collaborative design activities. Conducting an investigation into this issue and comparing the results to the research using student designers described in this thesis, could yield important findings on how expertise influences design collaboration.

2) Developing the methodology to enable the application of different kinds of measurements. In this thesis, a possible measurement of the connectedness of collaborative design activity has been proposed to show how the PMTA can be of use when trying to measure design processes. The exemplary measurement, however, used only three different types of data derived from the methodology (intensity and location of motion traces, ratio of contributed design moves, and linkage of design moves). The PMTA provides a multitude of different kinds of data that can be retrieved. The measurement of connectedness used in this thesis was able to reveal insights into the differences between design processes using three-dimensional prototyping media and sketching as the control condition. Different measurements, building on the PMTA, could help to gain a more comprehensive understanding of collaborative design activities.

3) *Investigating whether the outcomes of design processes using three-dimensional or two-dimensional prototyping media differ in their qualities.* This thesis deliberately left out any aesthetic or functional evaluation of the artefacts from the individual experiments. It focused its interest on the way the participants collaborated when using different prototyping media. However, the differences observed in the ways the three prototyping materials and the control condition, sketching, seemed to influence the collaborative design process, beg the question whether they also show in the outcomes of these activities. Are the artefacts produced when using three-dimensional prototyping media more or less creative or radical? Are they more or less aesthetically appealing? Are they more or less sophisticated? Such

questions were avoided in this thesis, but seem to be of interest when evaluating the value of individual materials in the different phases of the design process.

4) Investigate collaborative design activity with functional magnetic resonance imaging (fMRI). Observations made in this research suggest that some form of thinking not amenable to verbalisation has taken place in individual instances. Earlier work, such as that by Lloyd et al. (1994), already found a decrease in the verbal rate taking place during the design process, when investigating concurrent verbalisation while solving a given design task. They concluded that different modes of thought are being incorporated in design activities. Research in other fields has suggested that even a distinction between novice and expert designers could be discerned. Amidzic et al. (2001), for example, observed that amateur and expert chess players were using different parts of their brains. The approach of using fMRI to investigate design cognition has been used earlier (Alexiou, Zamenopoulos & Johnson, 2009; Gilbert, Gonen-Yaacovi, Benoît, Volle & Burgess, 2010). Applying it in conjunction with PMTA could corroborate or refute whether indeed designers use some mode of thought not amenable to verbalisation, and where it could be localised as brain activity.

5) Develop an automatic recording and analysis programme based upon the PMTA. The PMTA visualisations generated in this thesis have been traced manually using the software programme IOGraph. This application allows one to trace the movements of a cursor on the computer screen. Apart from being very laborious to produce, this method of tracing the participants motions causes some variances in the resulting visualisations. The predefined rules of tracing the hand movements aim at gaining more or less congruent visualisations. However, recent research of Toivanen, Huotilainen, Chi and Seitamaa-Hakkarainen (2014) developing an automatic analysis method of the co-design process puts a more automated method of devising PMTA visualisations within reach, as by now it is not clear with what granularity motion can be captured, whether or not individual rules for automated tracing can be predefined in the application and what kind of output can be generated. But it appears that the technological conditions may soon allow for a fully automated generation of PMTA visualisations with more accuracy, congruency and quantity.

8.6 Summary & closing note

This thesis aimed to provide a better understanding of how different types of prototypes effect collaborative design processes, and particularly the 'quality' of the verbal and non-verbal interaction. It has observed design practice in different design studios and looked at observable design practices in controlled experiments. In doing so, it has offered insight into the important role prototypes play in collaborative design processes, particularly in design discussions, and how the materials used in their production contribute to the quality of interaction between designers. By adopting an experimental, design-specific methodological approach and developing a new method – the Proxemic Motion Trace Analysis PMTA – to analyse design processes in an integrated way, it has been able to offer valuable contributions to design research, design practice, and beyond.

The research documented in this publication touched a few important fields of interest. At the end of this thesis, however, the role prototyping plays in collaborative design activities, especially in verbal and non-verbal communication, is far from being conclusively investigated. Quite on the contrary, it has spawned a multitude of new questions and interests. In the end, the hope remains, that these questions will have raised the interest and scientific curiosity not only of the author, but of others as well.

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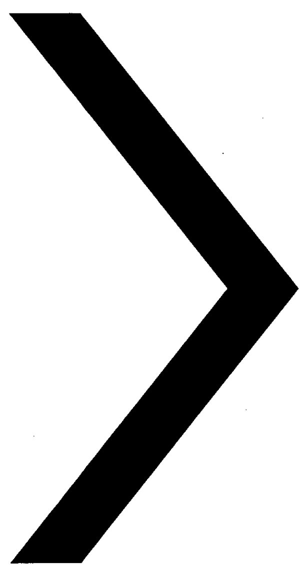


Appendix A – ethical approval

The Open University

From Dr Duncan Banks
Chair, The Open University Human Research Ethics Committee
Email d.banks@open.ac.uk
Extension 59198

To Andreas Peter, Department of Design, Development, Environment and Materials, MCT

Subject *"Prototyping in Collaborative Design Processes."*
Ref HREC/2012/1270/Peter/1
Red form
Submitted 20 September 2012
Date 24 September 2012

Memorandum

This memorandum is to confirm that the research protocol for the above-named research project, as submitted for ethics review, is **approved** by the Open University Human Research Ethics Committee **by Chair's action** as the project is considered low risk.

Please make sure that any question(s) relating to your application and approval are sent to Research-REC-Review@open.ac.uk quoting the HREC reference number above. We will endeavour to respond as quickly as possible so that your research is not delayed in any way.

At the conclusion of your project, by the date that you stated in your application, the Committee would like to receive a summary report on the progress of this project, any ethical issues that have arisen and how they have been dealt with.

Regards,

Duncan Banks

Dr Duncan Banks
Chair OU HREC

HREC_2012-#1270-Peter-1-approval-chairs-action

Appendix B – questionnaire

Questionnaire
«Prototyping in Collaborative Design Processes»

Name: ______________________________

Surname: ______________________________

Name of degree programme enrolled at CSM: ______________________________

Gender:
(please tick the appropriate box)
☐ Female ☐ Male

Language:
(please tick the appropriate box)
☐ Native English speaker ☐ Not native English speaker

	1	2	3	4	5	6	7	8	9	10
Number of years you have studied design: (please circle the appropriate number)										years

	1	2	3	4	5	6	7	8	9	10
Level of familiarity with other participant: (please circle the appropriate number)	Never met before				Meet each other occassionally					Meet each other every day

	1	2	3	4	5	6	7	8	9	10
Level of familiarity with proto-typing materials presented: (please circle the appropriate number)	Never worked with any of them before				Worked with some of them occassionally					Work with all of them every day

ual: university of the arts london central saint martins

The Open University

Appendix C – project information sheet

Project Information Sheet

«Prototyping in Collaborative Design Processes»

We like to invite you to take part in our research. In order for you to get a clearer picture of what the project is about and what you would have to expect from your participantion, you will find some more details about the research in this information sheet.

What is the project about?
The study investigates how prototypes and different kinds of prototyping correlate with collaborative design processes, specifically the quality of discussion. The research collects and analyses conversations and prototyping in a controlled experimental setup. In doing so, it aims at gaining a deeper understanding of how prototypes interact with different qualities of discussion. In the end, the research should be able to give an answer to the question: «How do different types of prototyping contribute to collaborative design processes, particularly the ‚quality' of discussion?» This is important because in order to tackle complex problems, designers need to collaborate and thus discuss design solutions, and the role prototypes and prototyping play in informing such discussions and collaborations still represents an under-researched area.

Why am I invited?
In order to conduct this research, we invite second-year BA and first-year MA students from Central Saint Martins College to participate. Participation is entirely voluntary.

What would I have to do?
The data for this research will be collected in a series of 25 controlled experiments, which will take the form of individual one-hour workshops. As a participant, you would take part in one workshop where you would be paired with another volunteer and asked to find a solution for a predefined design task. The main differentiation regarding prototyping techniques is focused on sketching and 3D prototyping. Thus, you would be asked to work out your solution either using sketching, 3D prototyping or without any external, visual representation. In addition, you would be asked to fill out a short questionnaire after completing the design task, stating whether you knew your collaborator before, if you were familiar with the prototyping techniques used, and how long you have studied design already. The workshops will take place at Central Saint Martin's premises, so no additional travelling will be required.

What happens to the data and the results of the study?
The individual workshops will be video and audio recorded. Fieldnotes and photographs might also be taken while the participants work out their design solution. Additional information is being collected by the brief questionnaire. All of these data will only be used for research purposes and publications. No other application of the data will be allowed. The anonymity of the participants will be protected by changing the names and by storing the data linked to the real names separately. The data itself will be stored on a designated and password-secured hard disk. The participants will be asked to sign a form of consent for the use of the recorded material.

What is in it for me?
As a small compensation, you will receive £ 15.- for taking part in the research. In addition, you will receive the results of the project, in the form of any publications resulting from the study.

What if I invent something important during a workshop?
It is possible that you invent something you might want to realise as a personal project later on. Therefore, all intellectual property rights on the ideas and concepts produced during the individual workshops will remain with the participants.

Who is conducting the research?
The research is being conducted as a cooperation between Central Saint Martin's College and The Open University. The study's primary investigator is **Andreas Peter.** He may be contacted regarding any questions with the project under: a.peter@csm.arts.ac.uk

If at any point questions arise about the conduct of the study, the following supervisors may also be contacted:
Prof. Peter Lloyd, Professor of Design Studies, The Open University: p.lloyd@open.ac.uk
Prof. Janet McDonnell, Associate Dean of Research, Central Saint Martins: j.mcdonnell@csm.arts.ac.uk

ual: university of the arts london central saint martins

The Open University

Appendix D – design brief

Design Brief
«Prototyping in Collaborative Design Processes»

Company Profile
Essetis is an international electronics manufacturer specialising in surprising, simple-to-use and stylistic products for everyday life. To foster its market position, it aims to provide unique offerings by merging products and services into new and unconventional design solutions.

Customer Insight
Recent customer research has indicated that people increasingly seek connectivity with friends and loved ones. However, modern day professional life increasingly forces people to move away from close friends and relatives. Modern technologies may help to bring these people closer together again in their everyday lifes through transmitting big and small gestures of care.

Design Task
Essetis is looking for some good concepts with which to develop a device to meet this emerging market. Your task is to develop a concept that allows people to connect with each other over a distance – within a city, within a country, or globally – in a simple and unique way in their everyday lives, by conveying small gestures of caring, loving, or support. Think of new ways and forms of communicating without copying existing solutions such as mobile phones, facebook, etc.

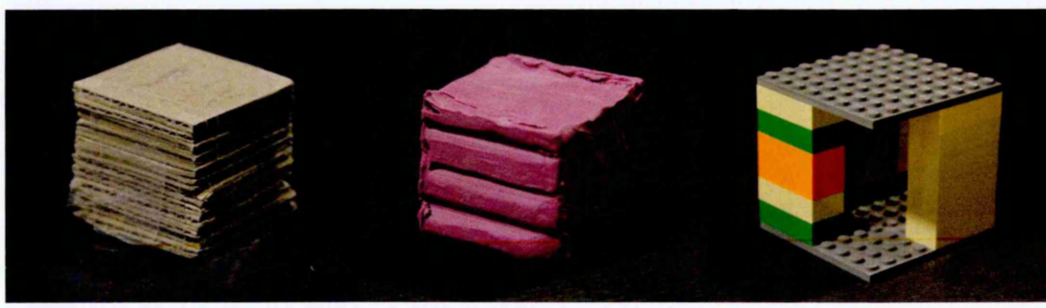
Workshop
a/ Familiarize yourself with the different materials available by constructing a cube with each of them. You have 5 minutes for each cube. Accomplish this task together.
b/ Using the materials available to you develop a concept together, in the form of one or more prototypes, that meets the requirements of the design task above. You have up to an hour to do this.

Specifications & Constraints
Use only the materials provided to develop a prototype of your concept. Use the materials in any way you like. Develop your ideas independently of what you think is currently possible technologically or financially.

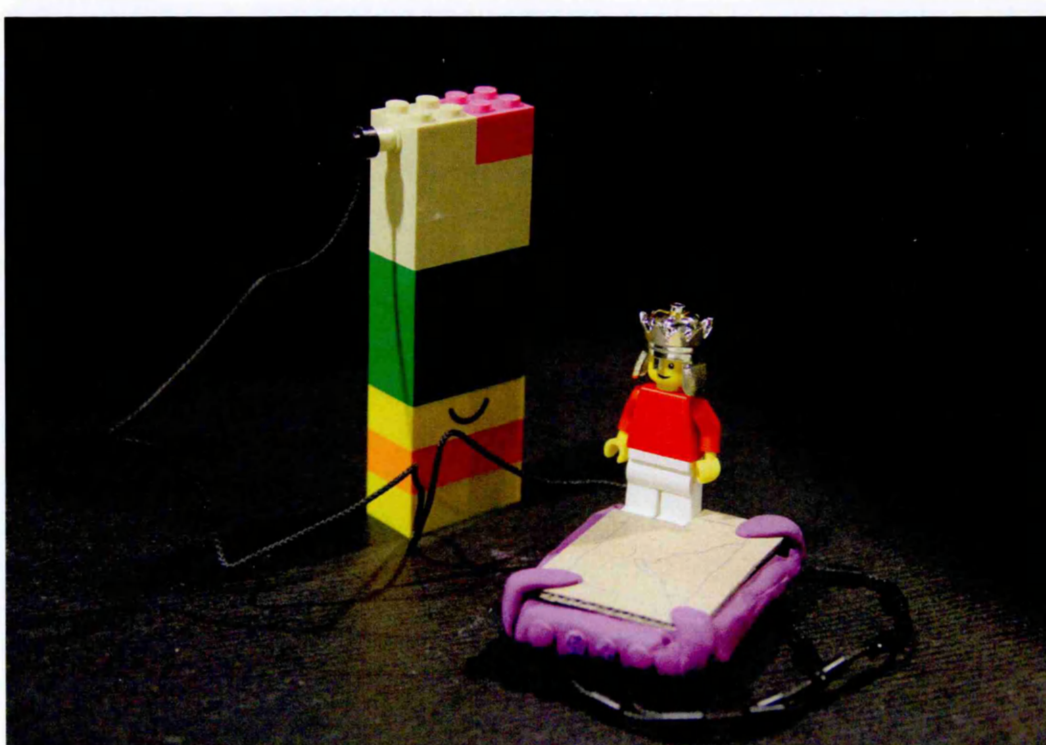
Appendix E – visual archive of artefacts produced in experiments

Experiment 1

Skill building tasks



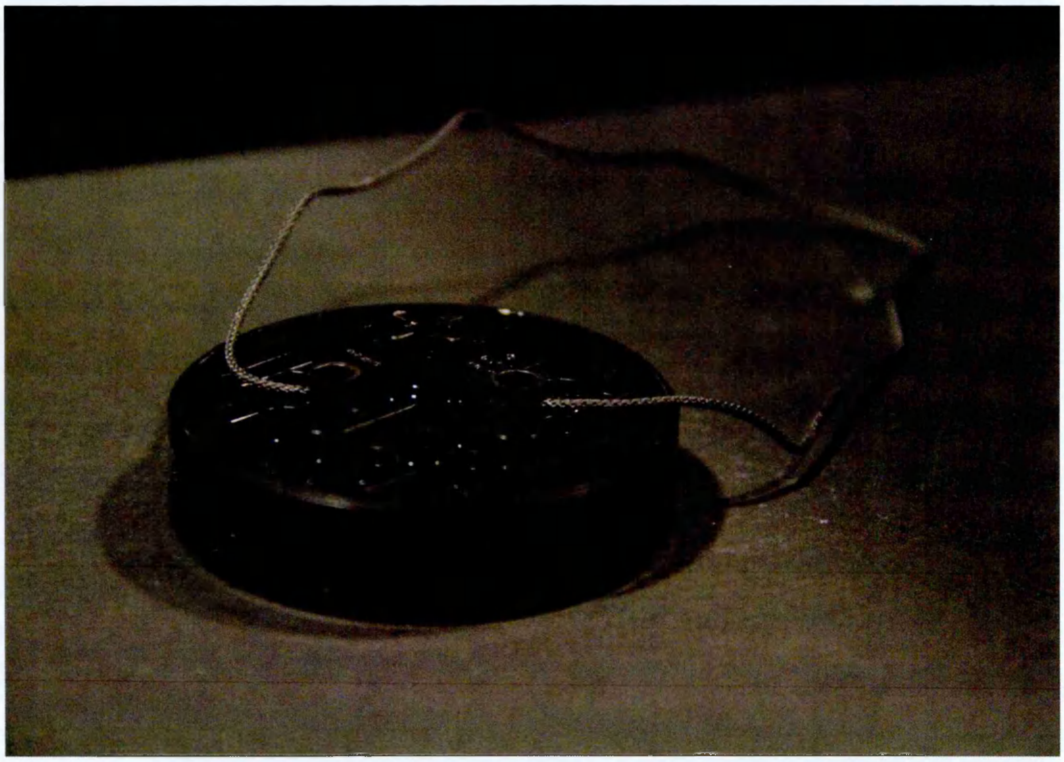
Main design task



Experiment 2

Skill building tasks

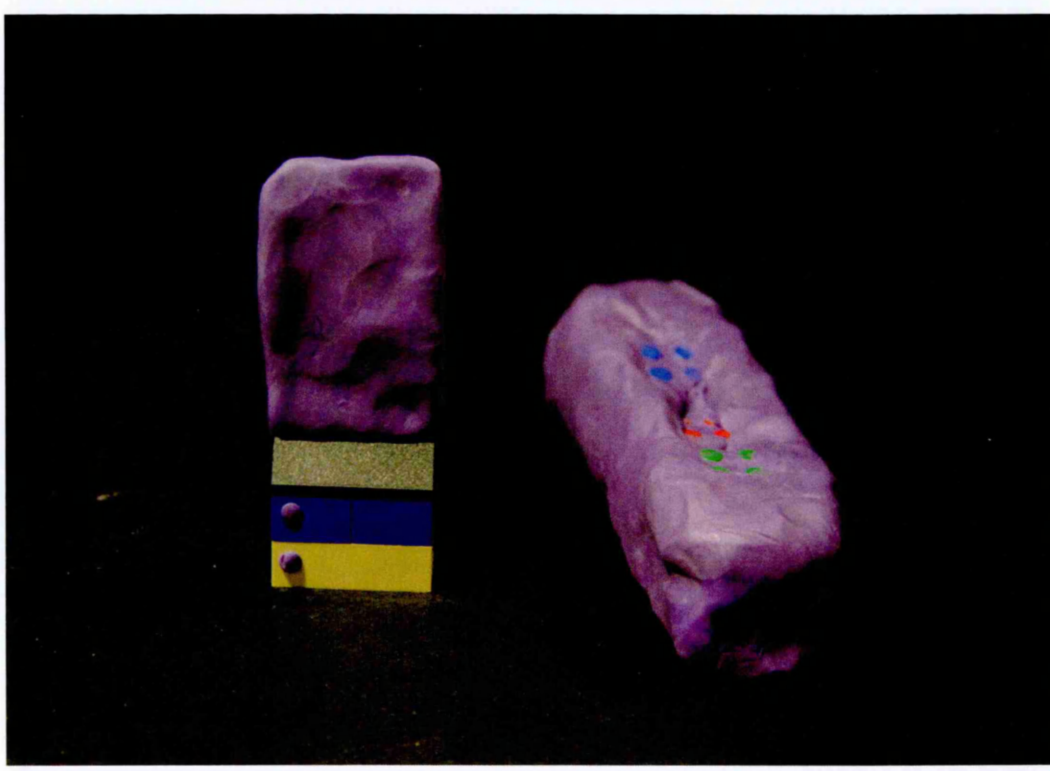
Main design task



Experiment 3

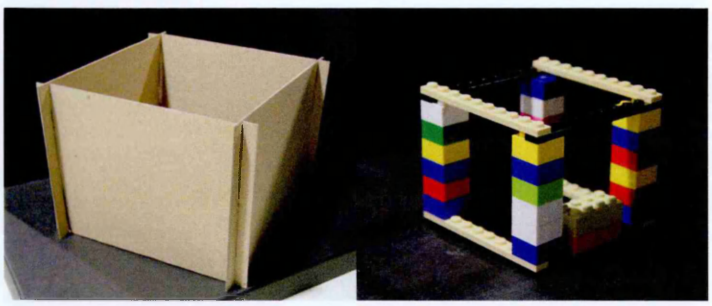
Skill building tasks

Main design task

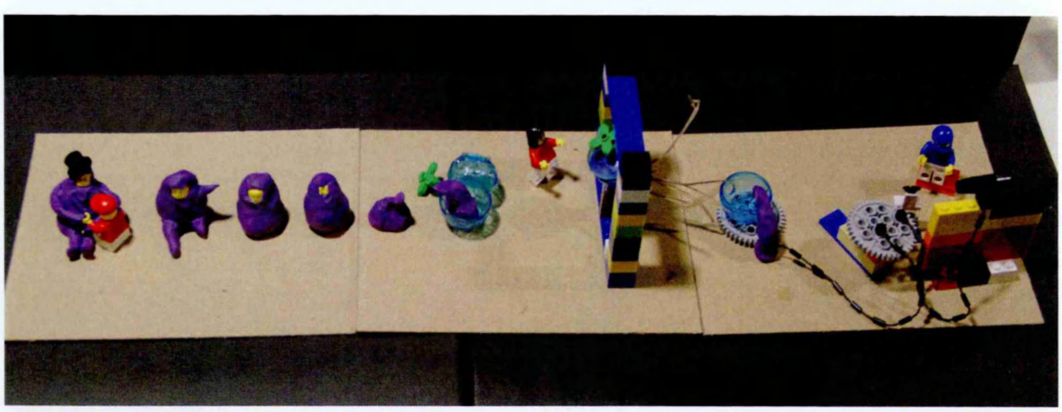


Experiment 4

Skill building tasks



Main design task



Experiment 5

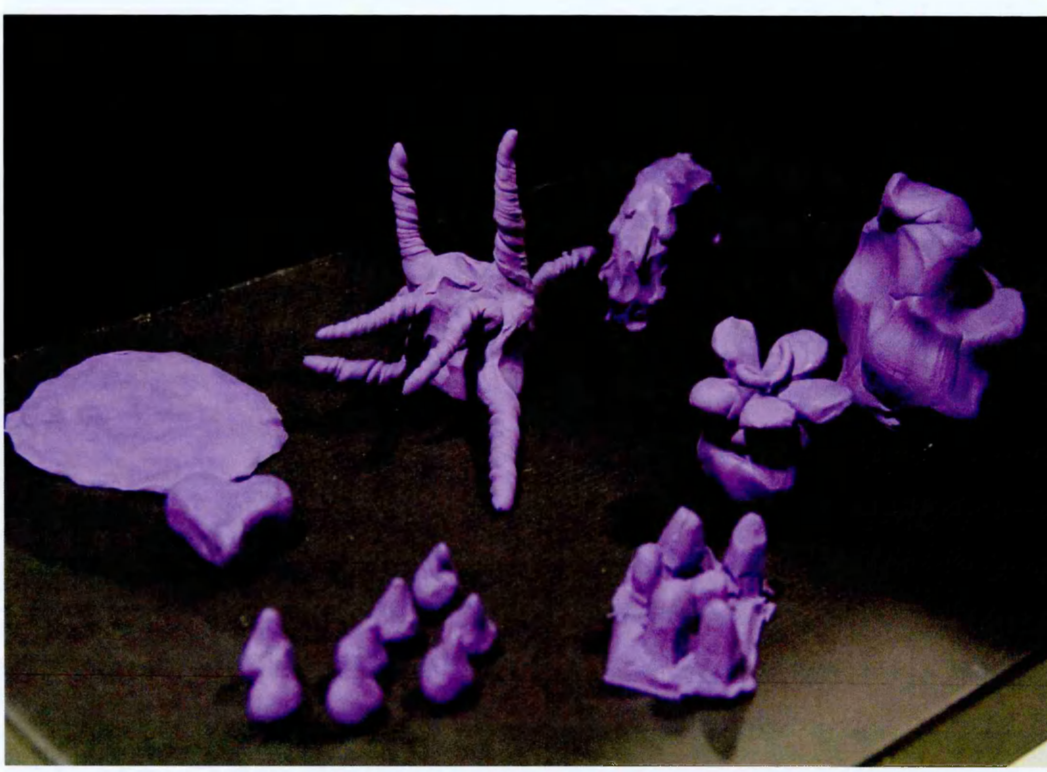
Skill building tasks

Main design task

Experiment 6

Skill building tasks

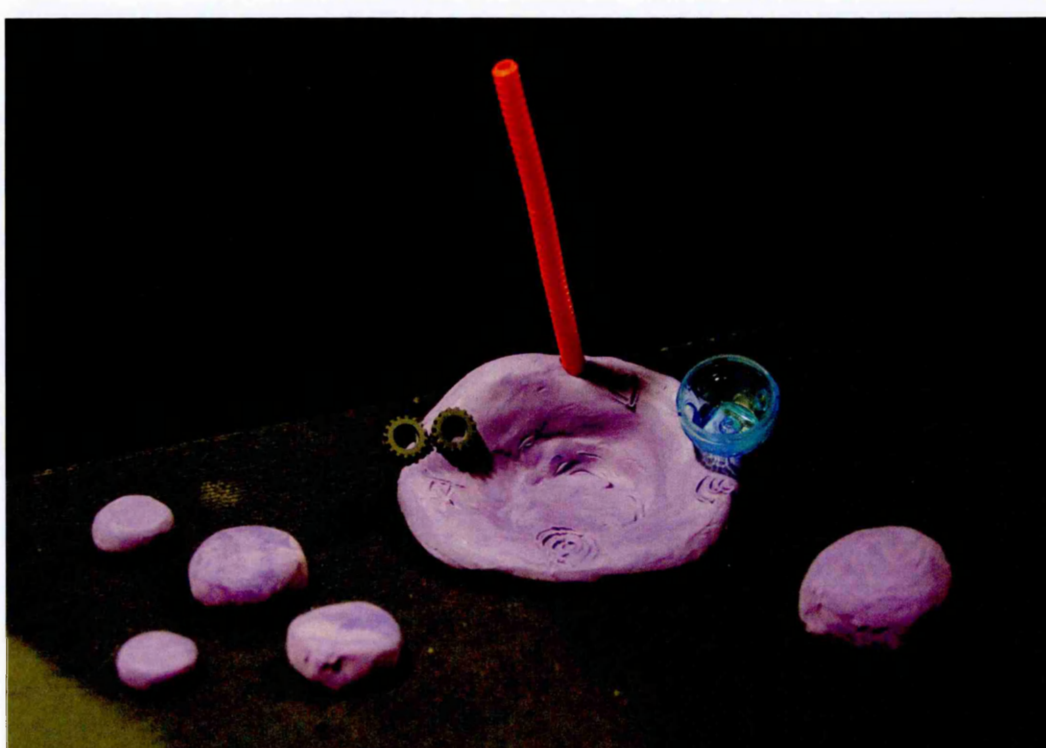
Main design task



Experiment 7

Skill building tasks

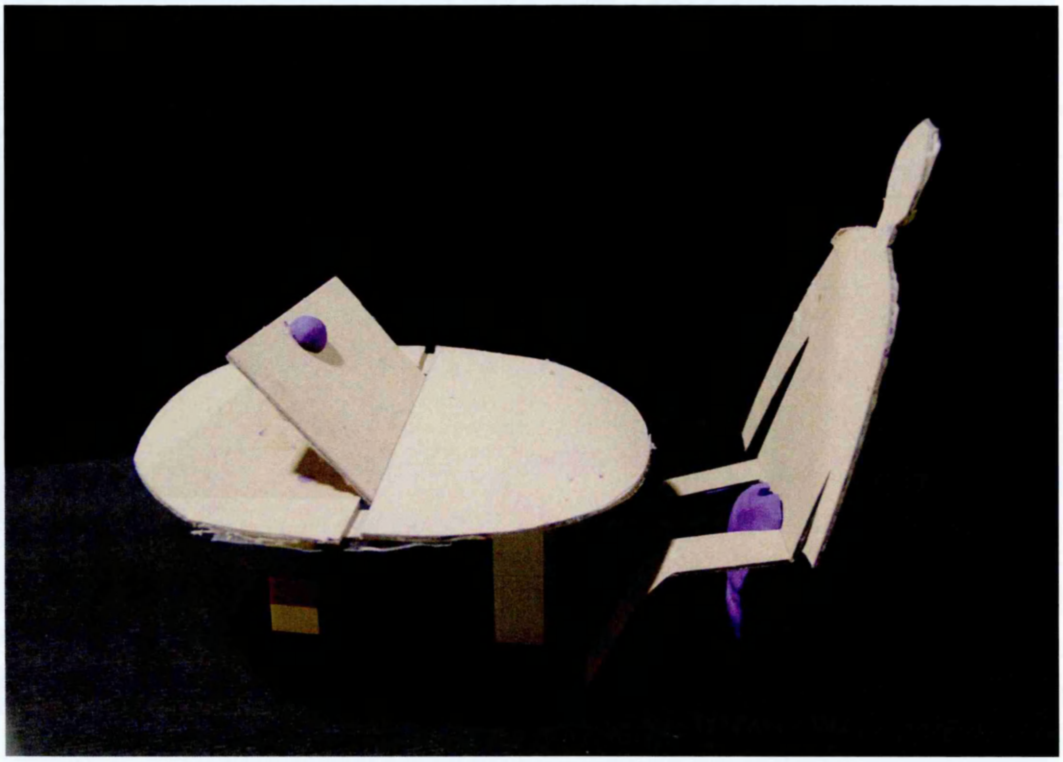
Main design task



Experiment 8

Skill building tasks

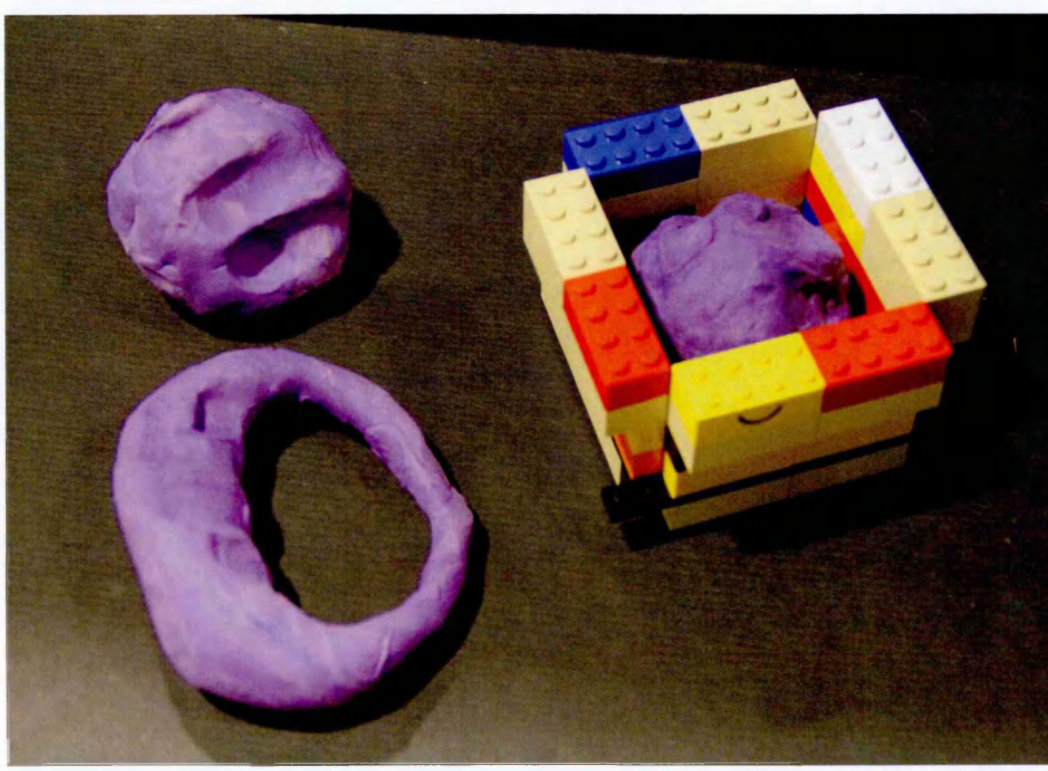
Main design task



Experiment 9

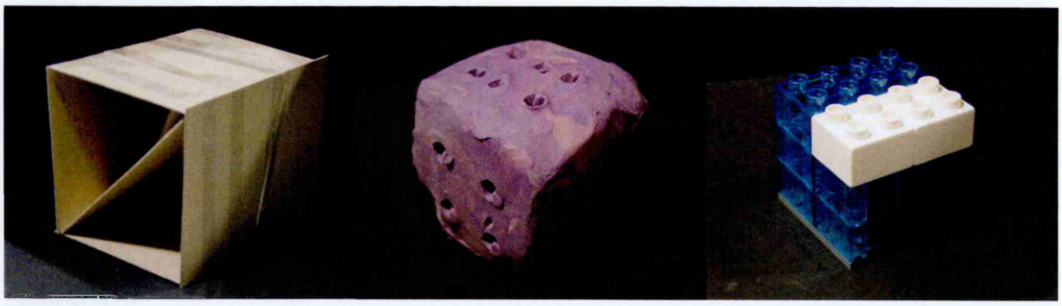
Skill building tasks

Main design task



Experiment 10

Skill building tasks



Main design task

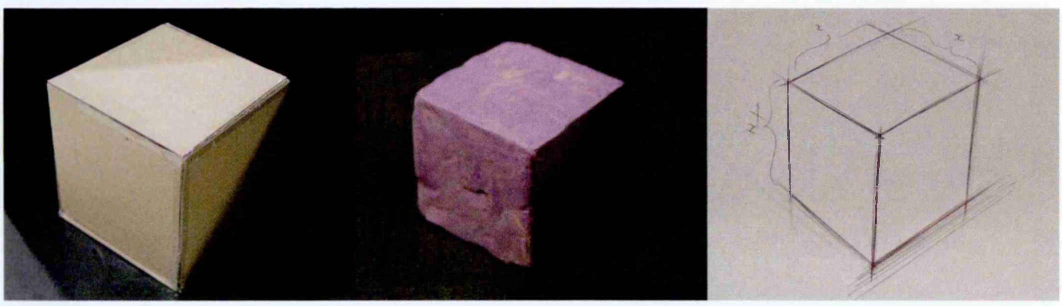
Experiment 11

Skill building tasks

Main design task

Experiment 12

Skill building tasks



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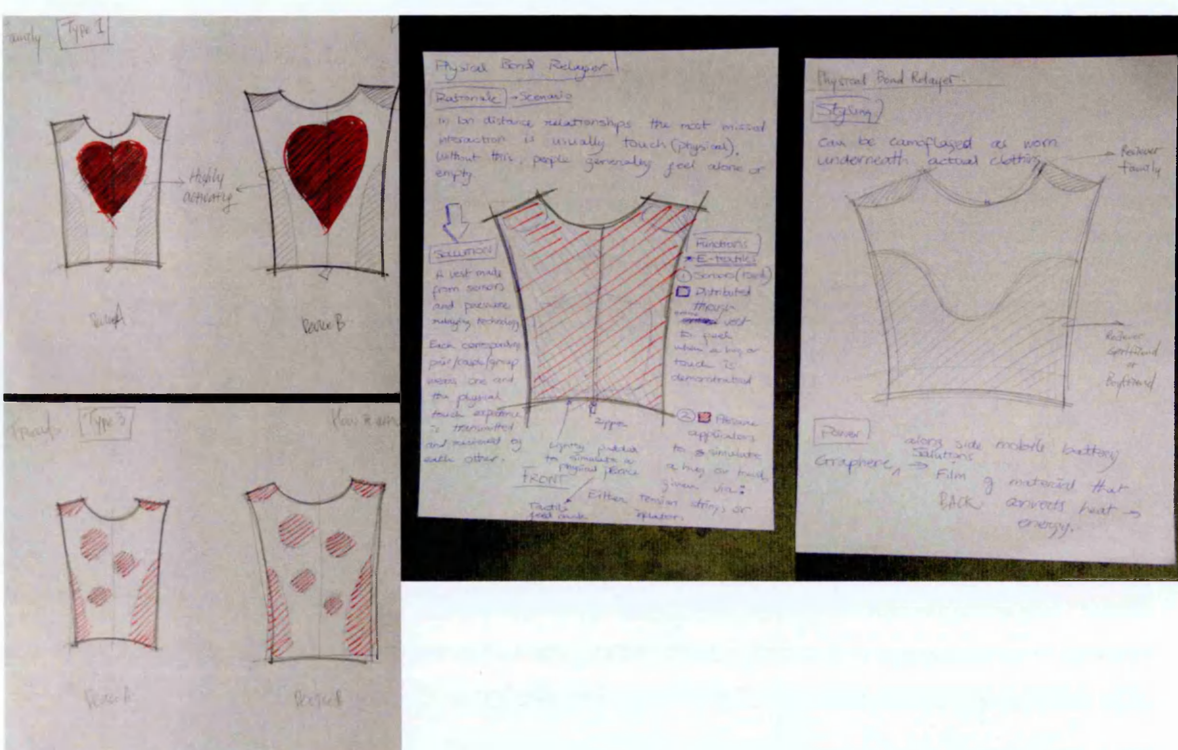
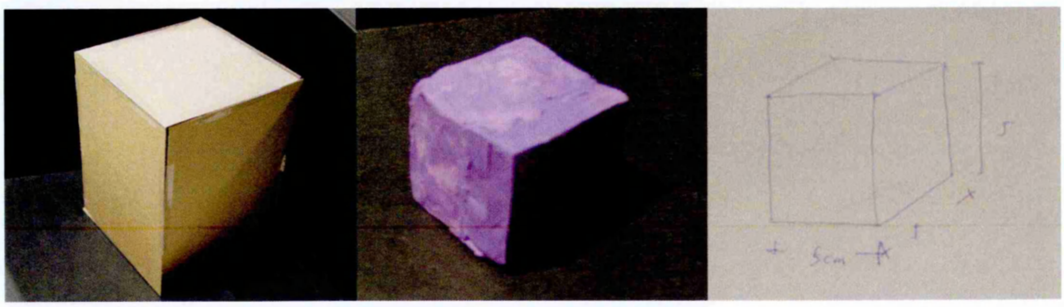
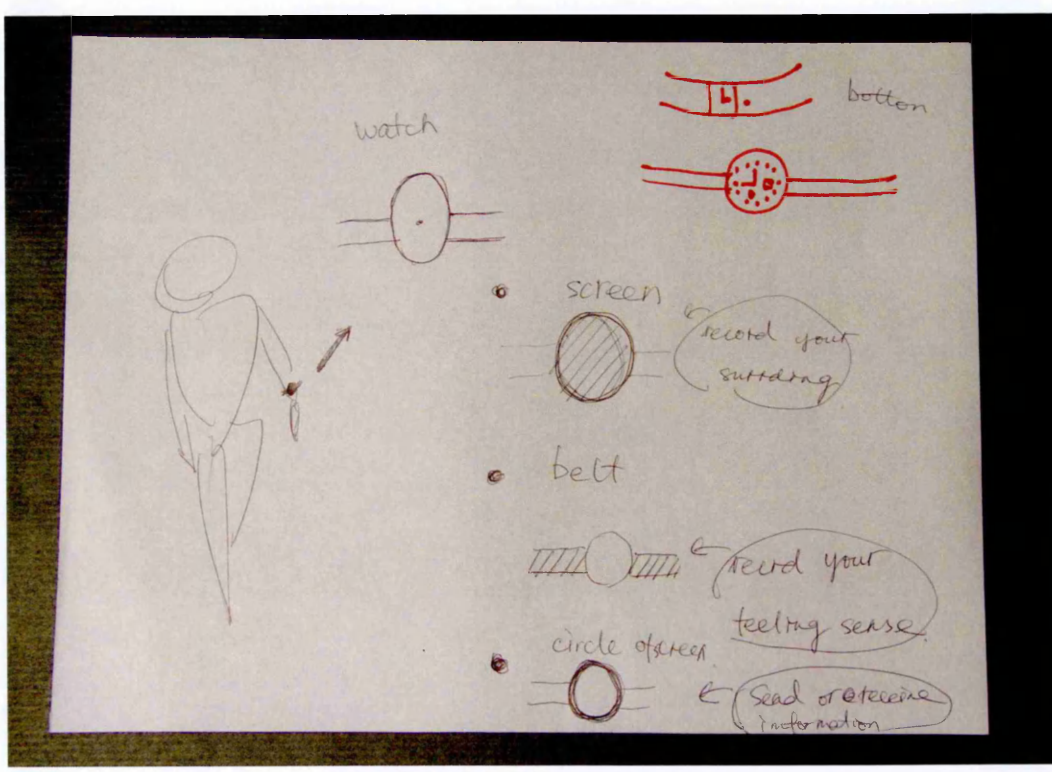


Experiment 13

Skill building tasks



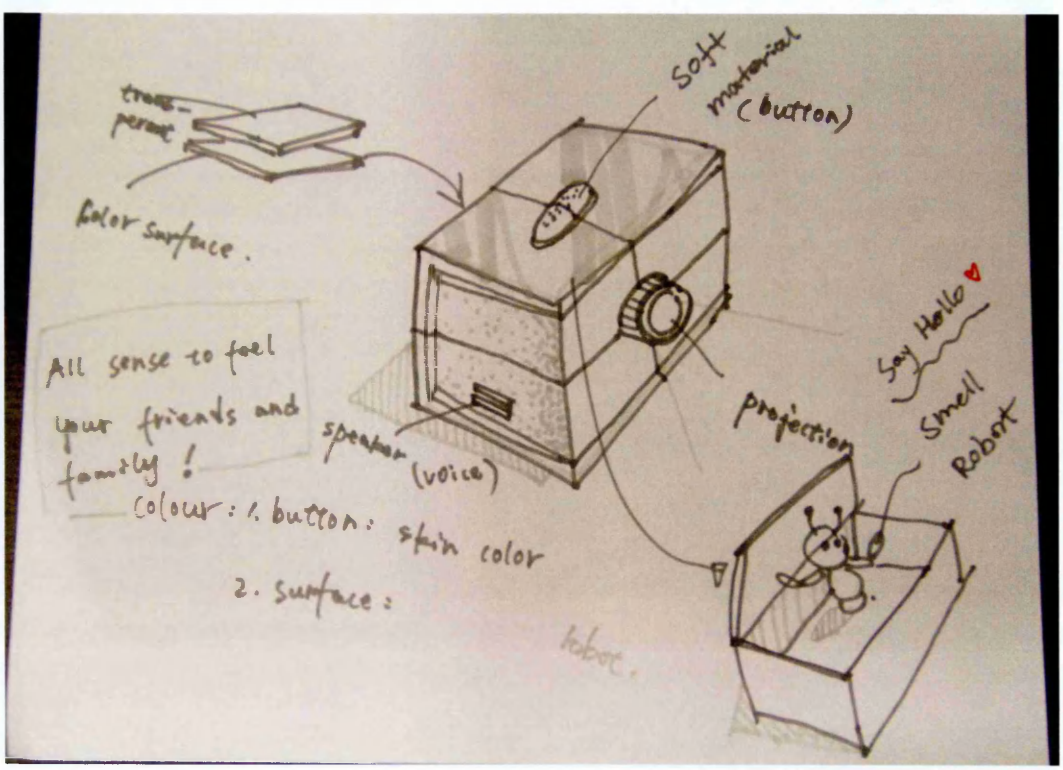
Main design task



Experiment 14

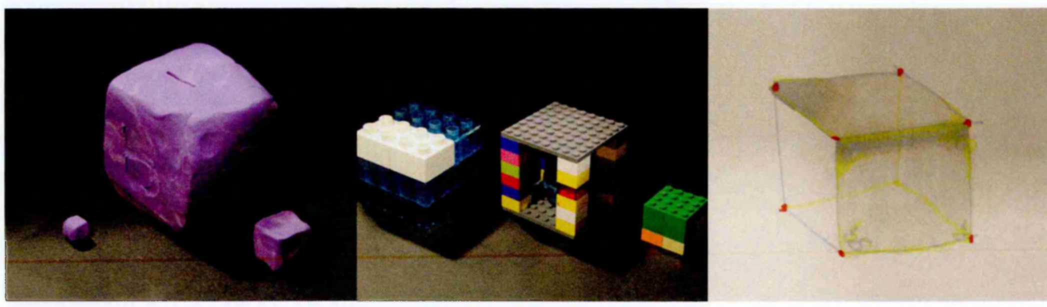
Skill building tasks

Main design task

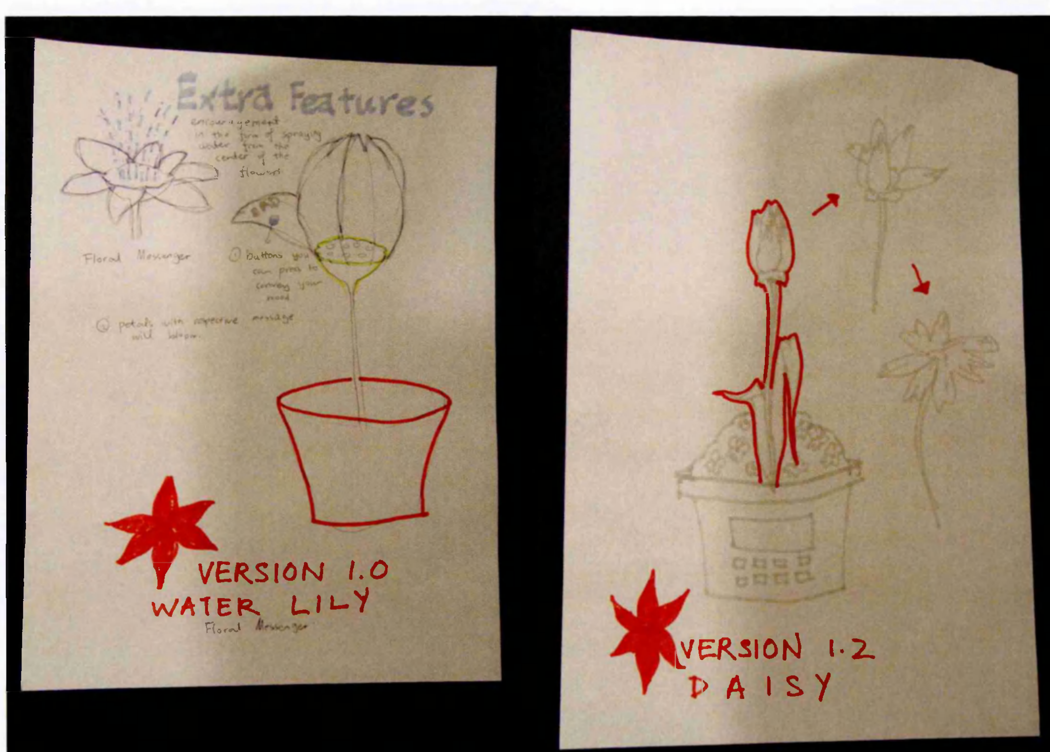


Experiment 15

Skill building tasks

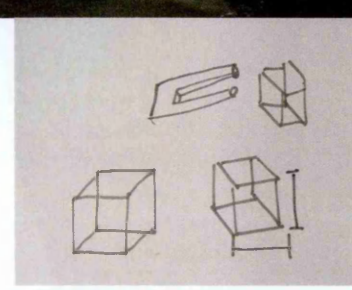


Main design task



Experiment 16

Skill building tasks



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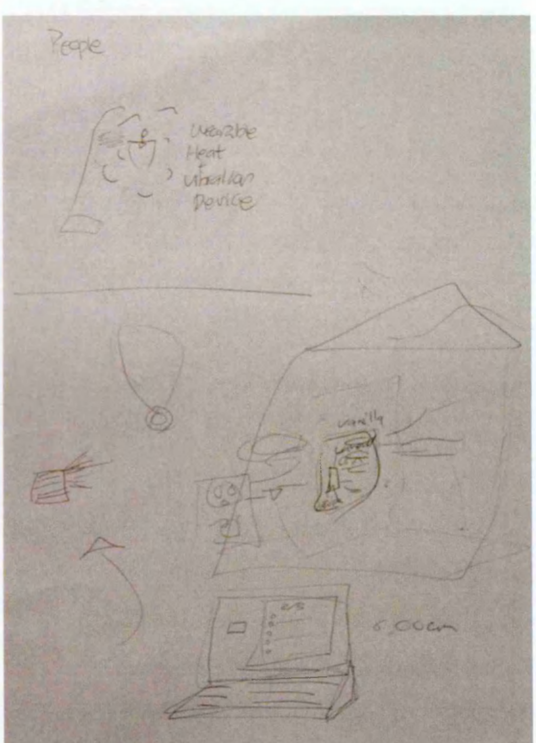
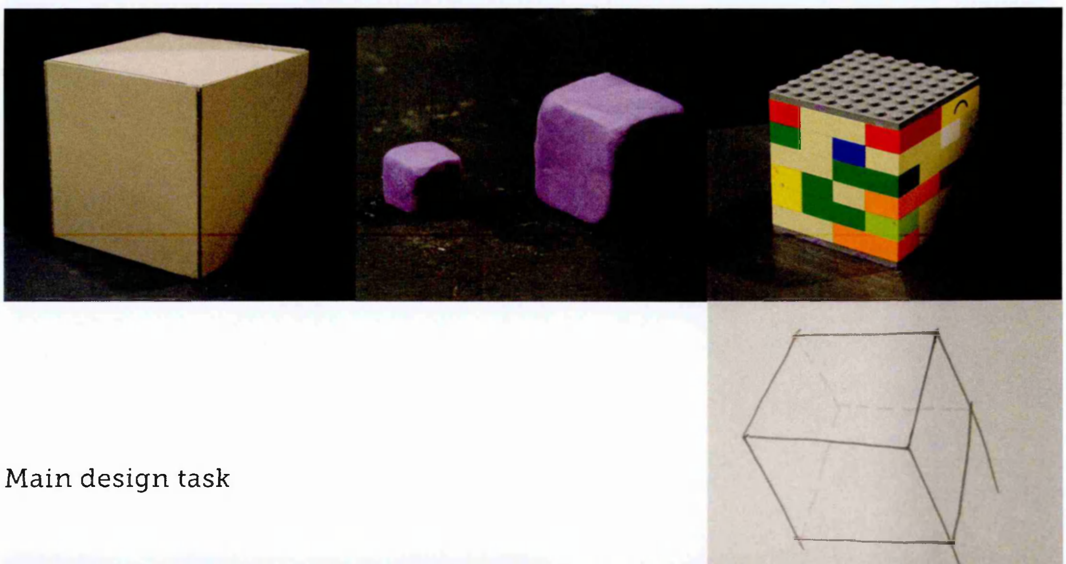
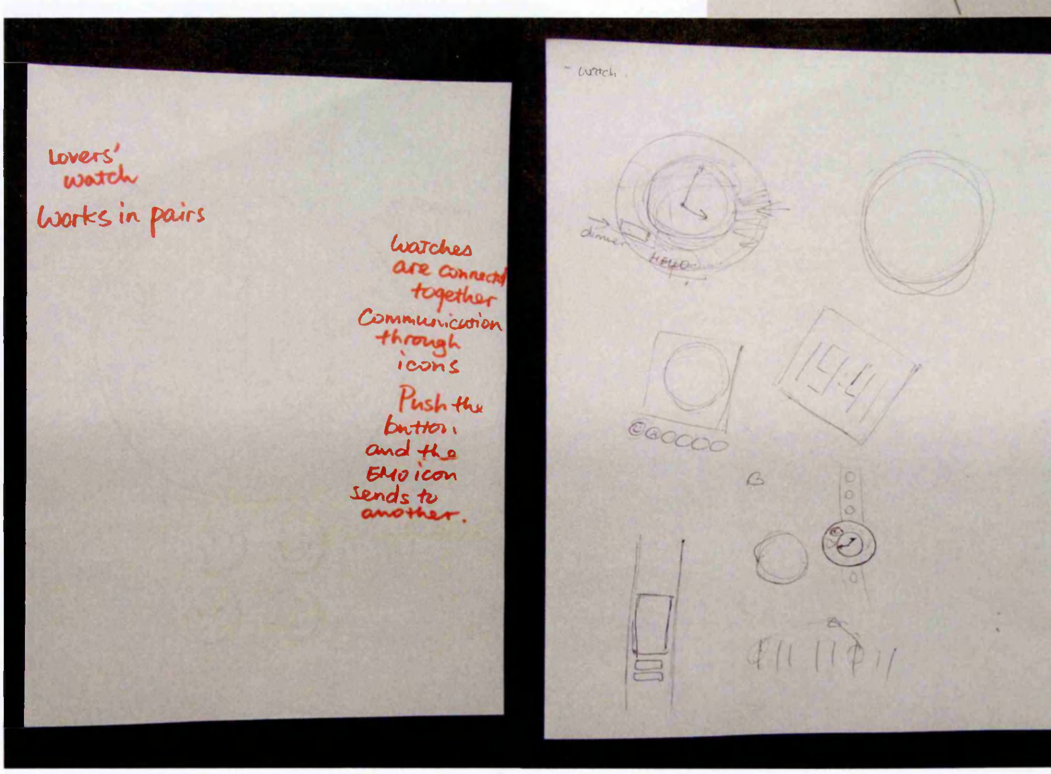


Experiment 17

Skill building tasks

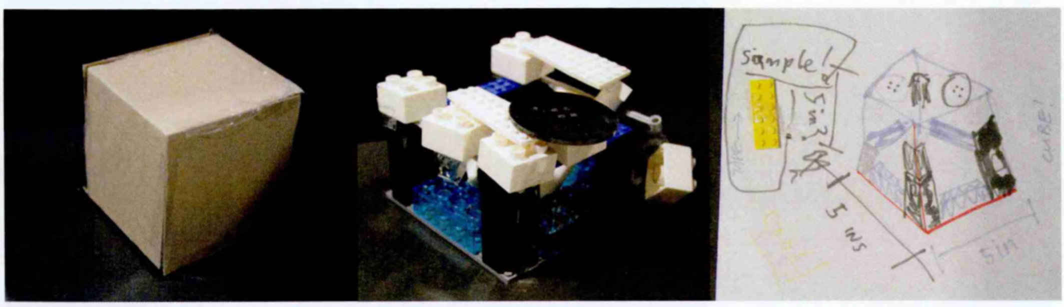


Main design task

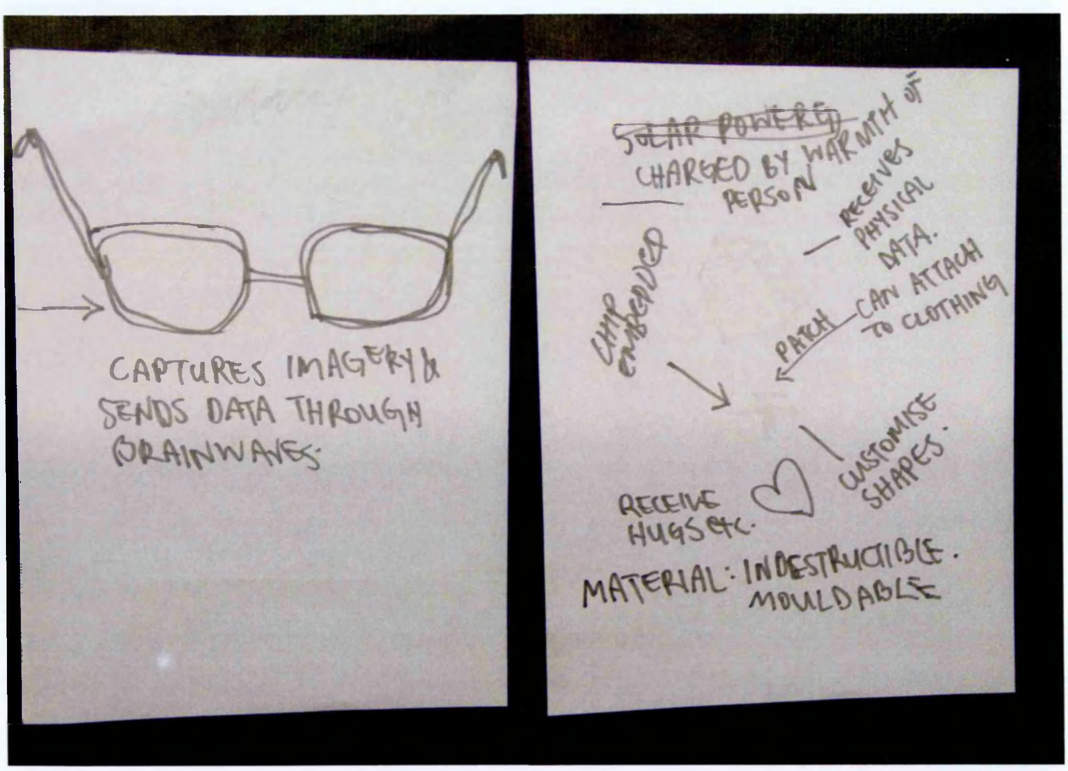


Experiment 18

Skill building tasks

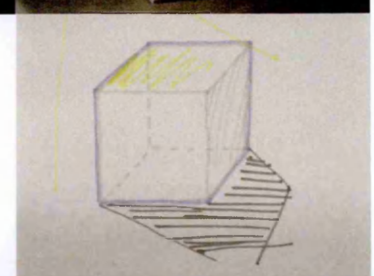


Main design task

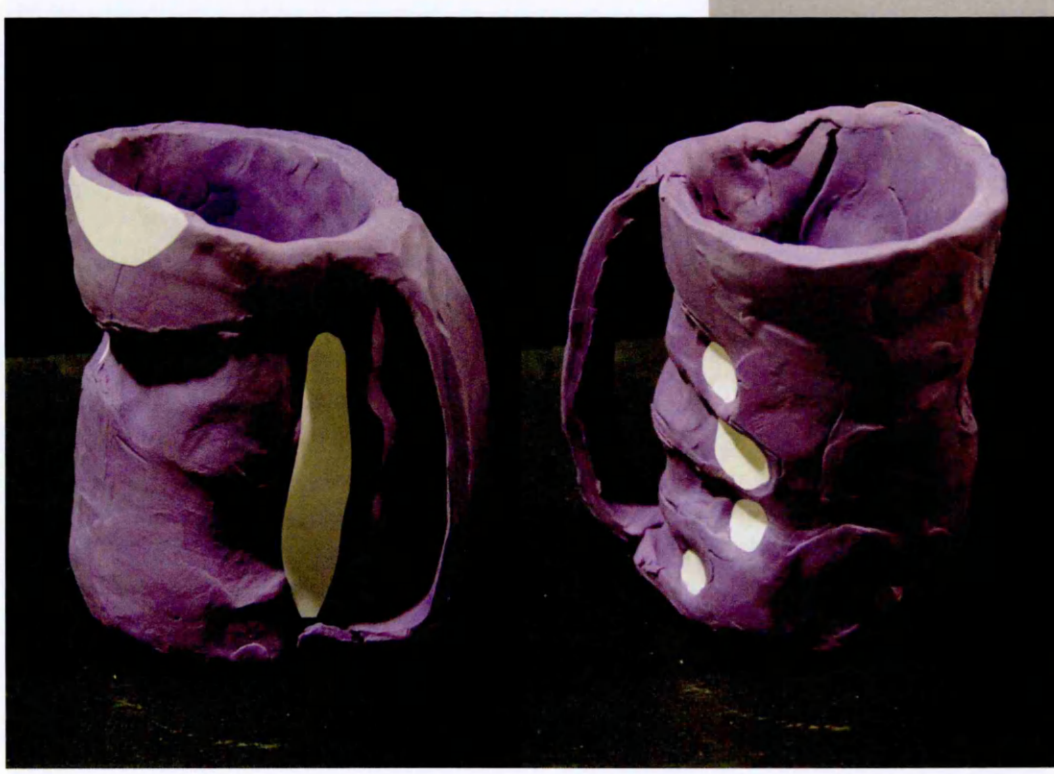


Experiment 19

Skill building tasks

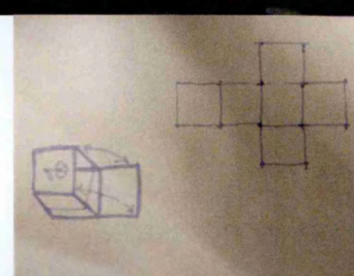


Main design task

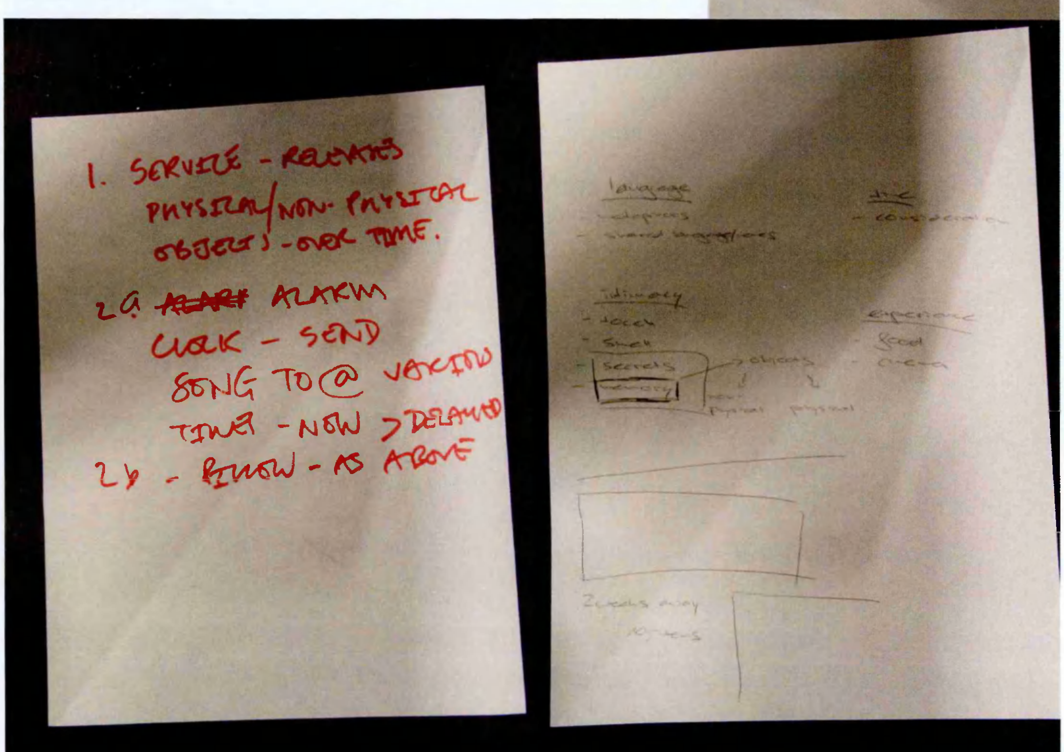


Experiment 20

Skill building tasks

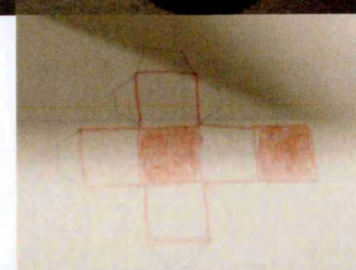


Main design task



Experiment 21

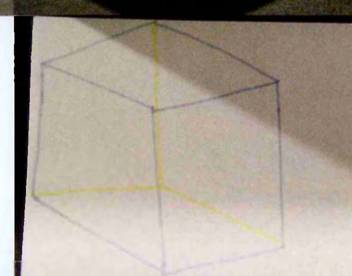
Skill building tasks



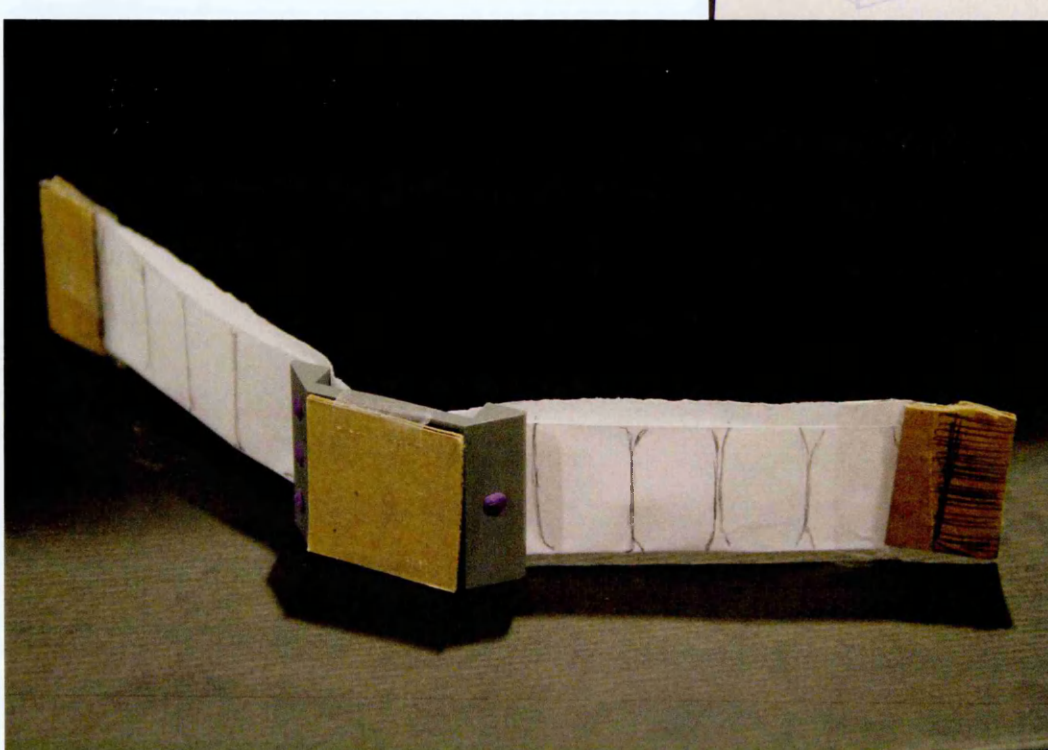
Main design task

Experiment 22

Skill building tasks

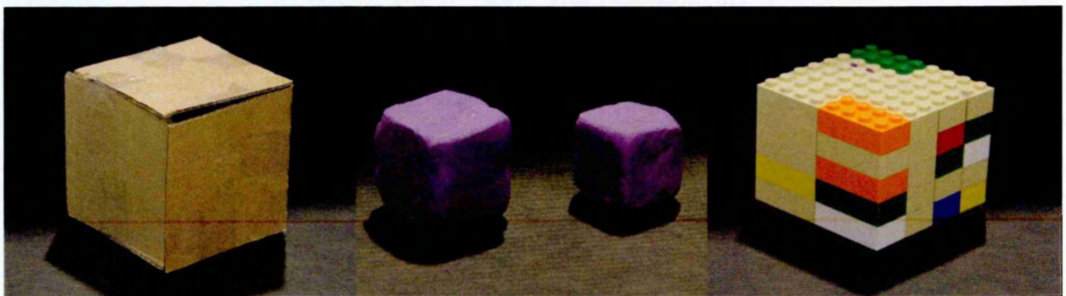


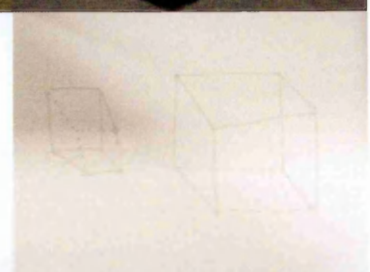
Main design task



Experiment 23

Skill building tasks





Main design task

Appendix F – field observations Studio Beat Karrer

Studio Beat Karrer

Analysis I

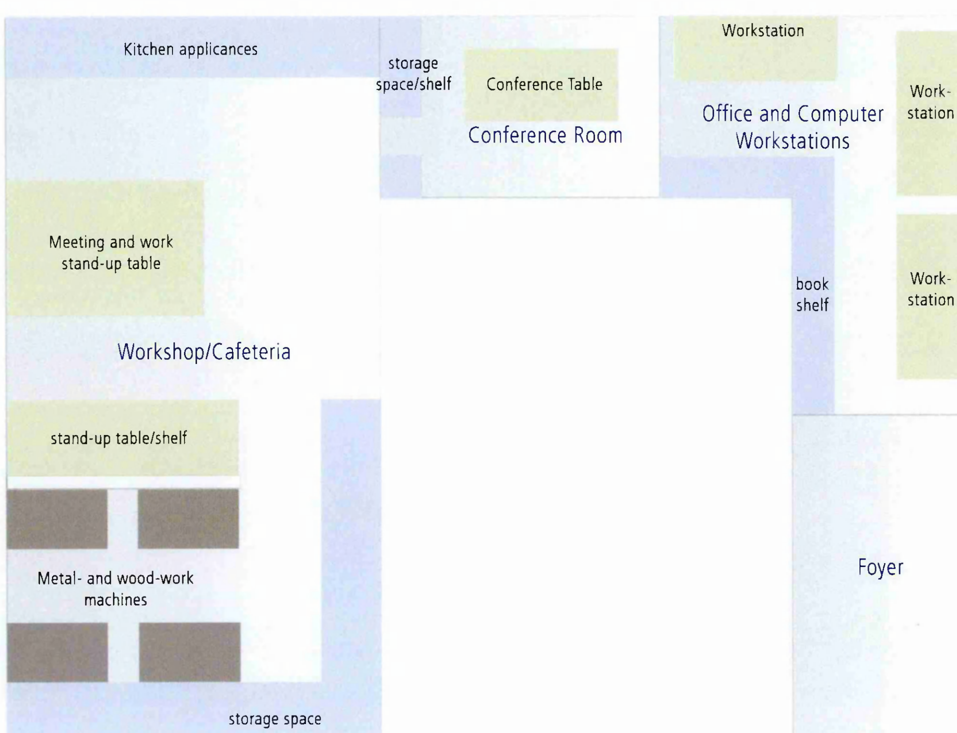
Introduction

The studio of Beat Karrer is a small design studio in Zurich. It is working in different fields, but a main focus seems to be placed on interior design objects, such as furniture, lamps, etc. Besides Beat Karrer three people are working at the studio, representing different fields of profession: a business developer, a biochemist, and a industrial designer. The founder himself has a professional background as a carpenter. He describes the development of the studio as starting out as a carpenter's shop with a heavy notion towards design, to a design studio with a heavy notion towards craftmanship. The first contact with the studios head Beat Karrer was established by Nicole, at a design conference in Basel.

The following notations represent some observations made during a first visit at the studio. The aim was to use the protoyping-centred model (see appendix) to categorise the findings along the four main topics culture, communication, conception, and coordination.

Culture

Location



The office space is being seperated in four to five different areas: the foyer, the actual office room, a conference room, and workship with an integrated kitchen. The foyer itself is being shared with two other businesses. Three different computer workstations are standing in the office as well as a large book shelf. Through the office the conference room is accessible. A conference table and some shelf space are standing in this room. Next to the conference room a large workshop with a few kitchen appliances along one side of the room is located.

The workshop itself is roomed with a large stand-up table (picture 1), a lot of storage space from floor to ceiling (2) as well as – separated by a wall – metal- and wood-work machines in the back of the workshop. The locations, especially the office rooms, appear bright and clean. The workshop a little less so. Some models of current or past works are being displayed on the shelves (5). The rooms atmosphere is rather down-to-earth and sober. Several prototypes are standing in the workshop (6). While in the office rooms a serene atmosphere prevails, the workshop does make the impression of a hands-on and craft-oriented workplace.

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Rituals/Actions

Not a lot of information could have been gathered at this first meeting about rituals and actions that would constitute the company's culture. At one point, the coffee machine was being labeled as the „most important machine in the studio". This might lead to the assumtion that a lot of informal meetings are taking place over a cup of coffee. Prototypes and sketching paper lying on the stand-up meeting table next to the coffee machine somewhat support this interpretation.

Standards/Styles/Preferences

As Karrer was explaining, the studios preference is to move very early to prototyping and experimenting with materials. CAD is only used very late in the development process, mostly for representational purposes or to test a specific functionality of the future product. Referring to the stylistic preferences, the work is aiming at minimalistic yet elegant solutions.

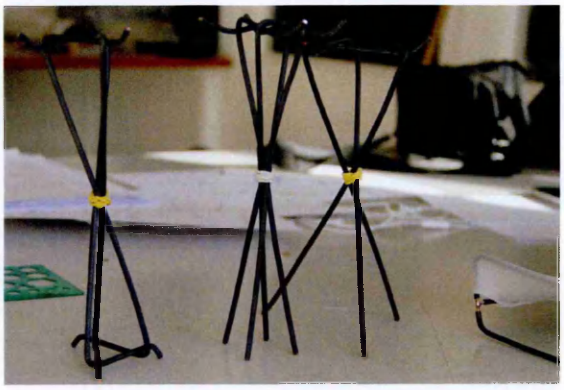
Communication

Tacit/Informal Information

Through its early move to the prototyping with different materials, a lot tacit knowledge may embody itself in the work, Karrer explains. He feels a strong need to touch the individual materials, to shape them and learn from the materials reactions. In this perspective, tacit information is being represented in and communicated througt the prototype itself.

Use of prototypes

Prototypes are being used for a variety of different purposes by the studio: to show a specific functionality, to represent a shape or form, to test stability, etc. The pictures below show a few prototypes made for a hallstand. Picture 1 shows the early prototypes made for the early testing of the shapes stability. Once a solution for the stability problem was found, a more refined model, incorporating solutions for other problems such as the joining of the elements (picture 2), was being made with the actual material that was intended to be used in the production (picture 2, 3).



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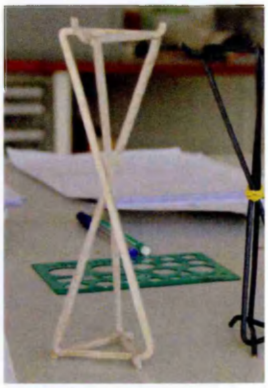

3

Prototypes are also being used in the studio to reflect on different effects and appearances of materials. Pictures 4 and 5 show how the choice of fabric and its colour influences the overall appearance of a chair, for example by producing different Moiré-effects.

4

5

Referring to the different categorizations of protoypes, according to Yang and Epstein (2005), these prototypes would mostly fit the describtions of proof-of-concept and proof-of-product purposes of prototypes. From a categorisation more focused on development stages – like suggested by Sommerville (1995) in Yang and Epstein (2005) –, the prototypes represented in picture 1 could qualify as throwaway prototypes, while the examples in pictures 4 and 5 could be described as evolutionary.

Regarding van der Lugts' (2005) variation of Fergusons (1995) categorization of thinking, talking, and prescriptive sketches to thinking, talking, and storing sketches, pictures 6 to 11 might give a good example of storing sketches. At the studio, this board was being used to categorise, store and make available for further use the findings of a research related to the design of future heating appliances. On the board are the research findings as well as first ideas, which emerged during the process, being stored.

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Conception

Problem Framing

In its work, the studio is constantly reflecting the objects/the designs relations to individual contexts. During the conversation, Karrer drew a rough sketch to illustrate this (picture 12). According to this view, an object must be viewed in relation to different situations, like the immediate surroundings of a specific room, the building, the city, the society or user and societal changes in general.

12

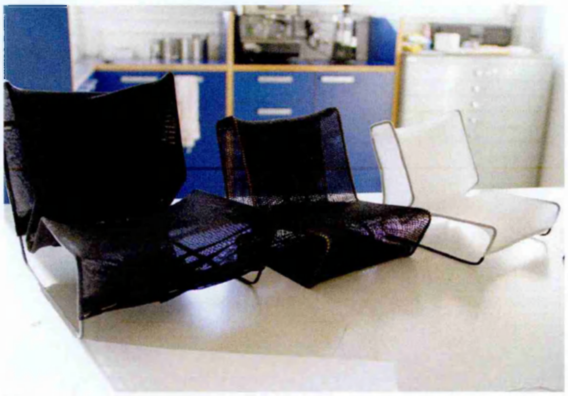
During the problem framing phase, usually a large quantity of sketches and first throwaway prototypes would be produced. The findings learned from these interpretations and re-interpretations would occasionally be reflected again in the different contexts.

Design Principles

In generalistic definition, the studio follows design principles derived from minimalism and the „form-follows-function" claim from the Bauhaus school. During this first conversation it was hard to discern the more specific underlying design principles. This might be achieved in a future case study at the studio.

Solutions proposed

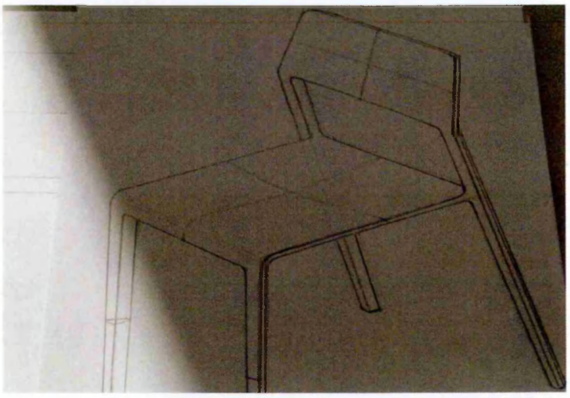
The solutions proposed in two incidents might support Karrers claim to focus strongly the materiality of products. Picture 13 show some of the prototypes made for a chair, which I mentioned above. These models study the effect of individual fabrics on the design.



13

Additionally, the studio is currently working on a plastic chair for a swedish furniture manufacturerer. The drawings shown in pictures 14 and 15 represent a design which takes into account the specific adavantages of the material, allowing a shape that is characterised by very slim lines along the edges. The same design made in wood, would according to Karrer, prove to be extremely difficult to achieve.

14



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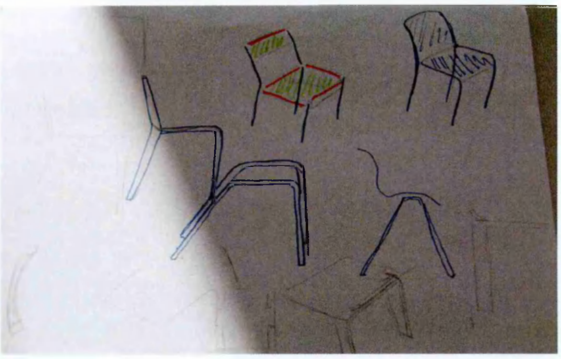
Coordination

Team

The team of Studio Beat Karrer consists of a biochemist, a business developer, an industrial designer and the head of the studio. The biochemists role is foremost located in research and development, mostly of new materials. The business developers function mainly comprises the generation of financial resources for individual projects. The industrial designer and the head of the studio work on the designs themselves. In this first visit, a more specific characterization of the functions and personalities was not possible. This might be an interest of a future case study.

Structure/Process

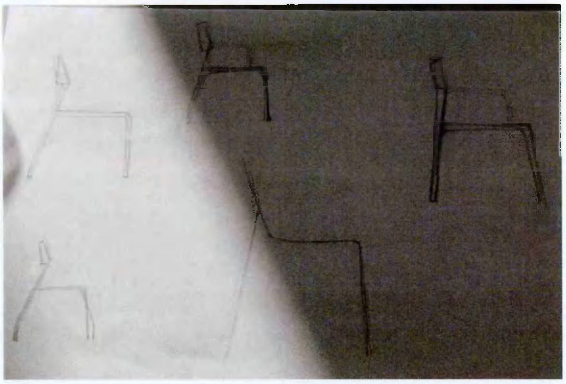
The process and structure of the work flow is usually defined by the studio's head upfront every project. The main phases are a first research into the problem, the briefing with the client (which is very much guided by Karrer himself), the subsequent deepening research and problem definition, and the refinement of the prototypes. Sketching and prototyping are being used very early on in this process, usually in the first phase. Picture 16 shows an early thinking sketch. An example of a early and quick prototype for a type of chair is seen in picture 17.


16


17

Tools & Methods

The tools and methods may vary in each project. The studio has a well equipped workshop with wood- and metal-work machines and materials. Used methods can be also very simple, like the use of serialised sketching, shown in pictures 18 and 19.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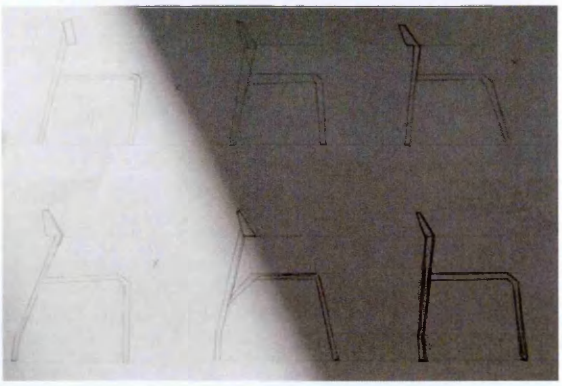
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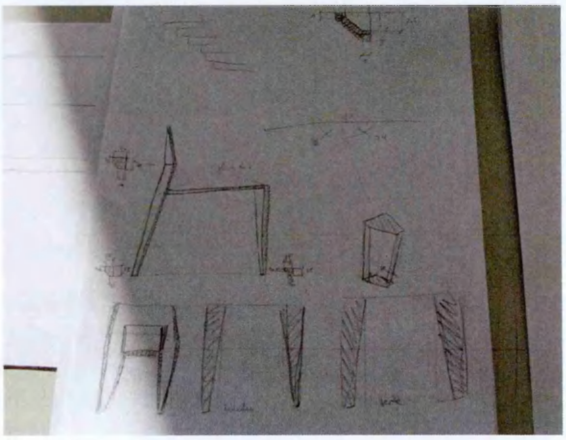
Sketching as a method is also being used to clarify more specific problems of an individual design, as seen is pictures 20 and 21.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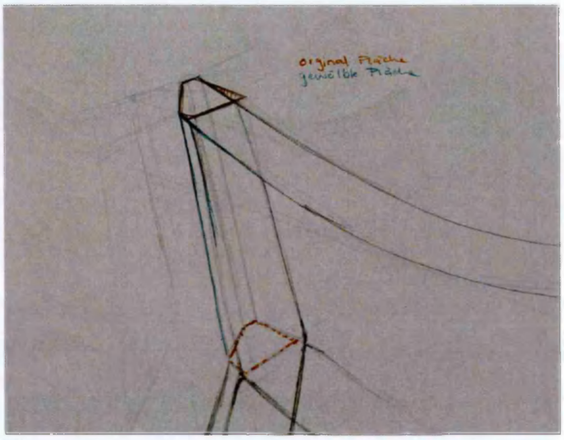

21

Analysis II

During the second visit at Studio Karrer, a stronger emphasis was being placed on the role of prototyping in the development process and the discussions of prototypes in meetings. Several different cases were discussed to shed light on different aspects of the topic. The informal interview was being recorded for later analysis.

Process model

Karrer explained that a basic underlying process model, the studio follows its own approach, called ‚Iconise'. The model identifies the individual steps as followed:

1	**I**dentify	Identifying the contextual situation, problems and constraints
2	**C**ollect	Collecting the relevant material, inspiration, observations and insights
3	**O**rganise	Organising and categorising the collected material
4	**N**ummerise	Nummerise of prioritise the organised material
5	**I**nterpret	Interpret the material to derive the most relevant insights and possible solutions
6	**S**hape	Building a shape according to the interpretation
7	**E**xpose	Exposing the prototype of finished product to test audiences or design experts

While most of the steps are being completed during a development process, their importance may vary greatly. Also, at times, the steps might change their order or are being repeated when contradicting insights are being gained in a later step. As the most important phases Karrer identifies step 1 ‚identify' and step 5 ‚interpret'. The work in these two steps is being done during team meetings. The tasks in the other steps are mostly accomplished by individual team members with the results being discussed in informal meetings.

In general, the prototyping process begins in step 5 (‚interpret'). However, insights gained from the prototypes may urge the designers to repeat one or more of the previous steps.

In the process, Karrer focuses mostly on the design and technology dimensions of a given situation. The business perspective is brought in by one team member, who works on a project-specific basis. Business aspects are most often being reflected in the work, as underlying principle (for example, finding a new way of production, which reduces costs) or prerequisits from the client.

Discussions/meetings

The steps 1 and 5, ‚identify' and ‚interpret', are, according to Karrer, crucial points where the individual group members meet for a formal meeting. While the client briefing and meetings most often only involve the studios head, he carries the information on into these meetings. The other process steps are also often being started and ended by meetings. However, these are carried out in a very informal manner, at a cup of coffee in the kitchen or at the goup members desks.

Karrer explains that the studios culture should encourage the open and honest exchange of opinions. At times, there may be an arguement on how an individual design should be carried out. These may or may not be resolved. Regarding conflicting views, one co-worker mentions that the studios head, Beat Karrer, sometimes takes design proposals to a client meeting, which he did not approve in the discussion. In the view of the co-worker, this is a sign of Karrers self-reflectivity – he may not always find the best solution himself – as well as of his respect to his employees.

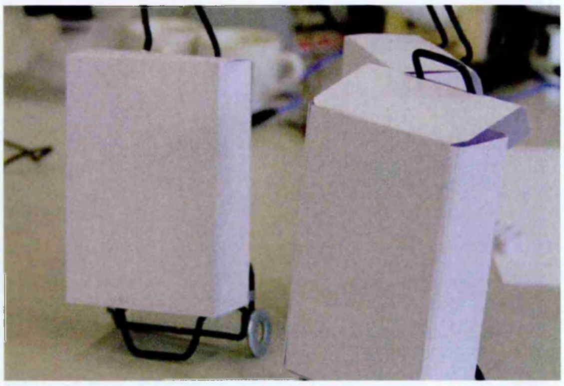
Most of the group discussions are taking place in the kitchen/workshop area, at the large stand-up table (1). More formal and client meetings are being held in the conference room (2).

1

2

Role of prototyping

Karrer points out the importance of a physical prototype in contrast to a mere computations CAD model: A physical prototype is more sensual and playful in the making and presentation (1 & 2). Often, constructing a rough model is faster to produce than a virtual representation (3 & 4). Especially the first does possess a great importance to Karrer. As he puts it, the advantage of a physical prototye is its „power of the real" („Die Kraft des Echten"). Karrer tends to move very early on from sketching to prototyping. As he experienced, a lot of problems are only being envisaged when moving from two dimensions to three dimensions – for example, how a specific material behaves, or a conjunction works etc. This observation might support a conclusion of the article XXXX, which observed the correlation of the early use of dimensioned drawings and design outcome.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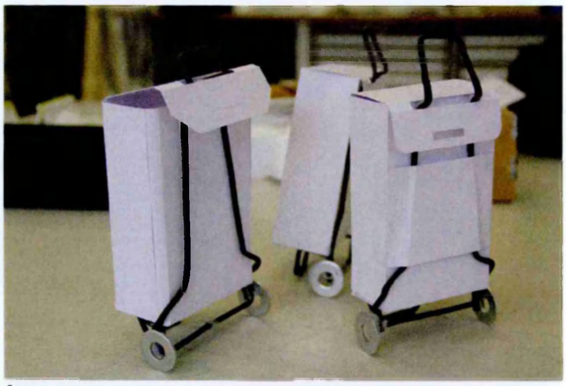
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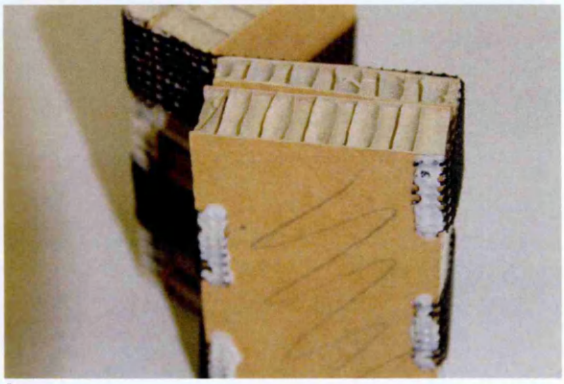
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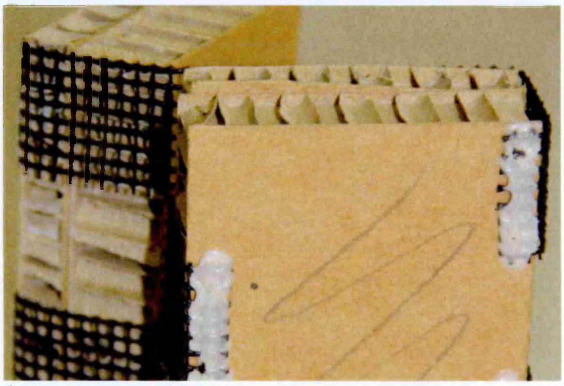
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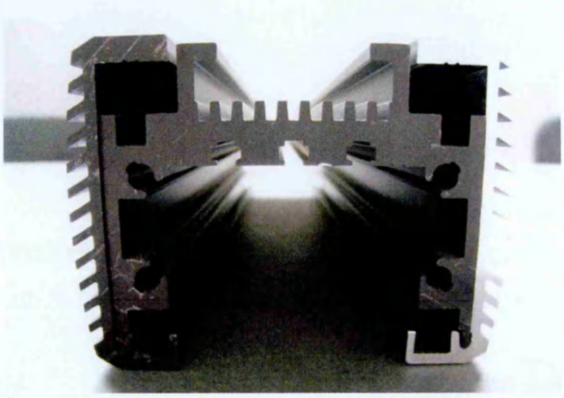
Also, Karrer prefers prototypes with fewer parts, which relates to the article XXXX that suggests a correlation between the parts of a prototype and the design outcome (5 - 8). As he put it: „When the building of the prototype is a tedious and difficult work, chances are that the production of the definitive product will be too. Which isn't preferrable..." As an example, Karrer presents the model of a LED lamp the studio had designed. While he central piece of the lamp consists of very few parts, the design solution with its gills allows and its increased amount of surface for a better heat distribution and thus a longer life of the LEDs as well as it gives the user implicit and tactile information of the use and direction in which the lamp is working.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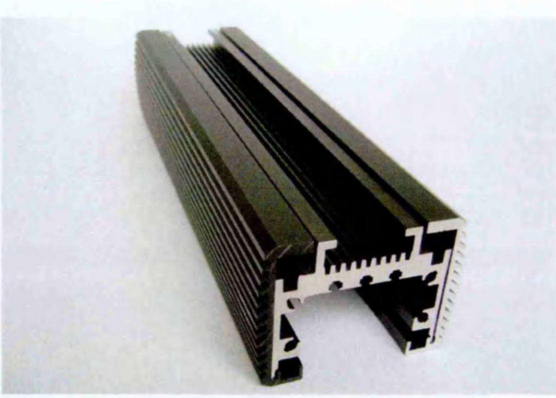
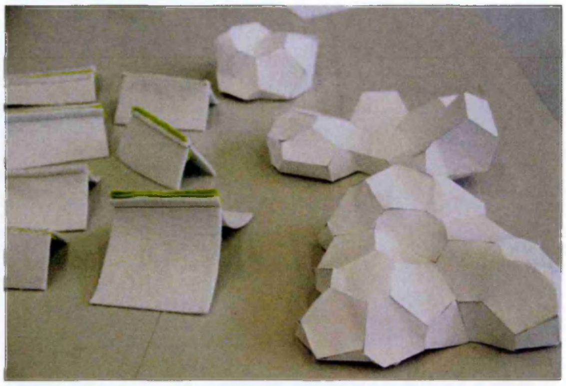

6

Karrer distinguishes two major categories of protoypes in his work: functional or technological prototypes (3, 4, 10, 11), and stylistic prototypes (7, 8, 9). The first demonstrate and test a technological solution. The second demonstrate and test a formal, aesthetic solution. However, he does not regard the borderline between what should be considered a sketch, a model, or a prototype as a definitive one.

The functional and stylistic prototypes are being mostly developed simulatenously, while the functional prototypes tend to be made a little bit earlier. Karrer shows this on the example of a new lounge design (7 - 11). In this case, the design aiming at the appearance and features of a rock at a beach, which offers many different seating options, is divided in two directions: the stylistic dimension, testing different shapes the couch may have (7, 8, 9), and the functional dimension, testing different ways of joints (7, 10, 11).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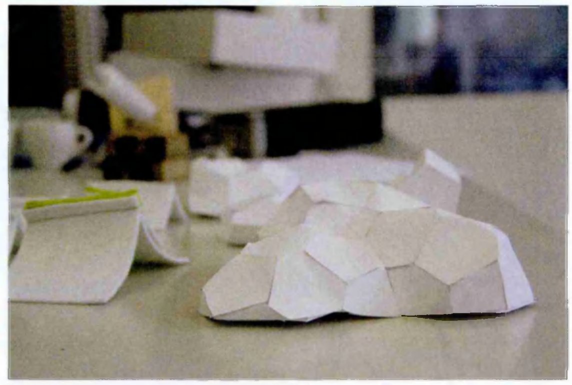
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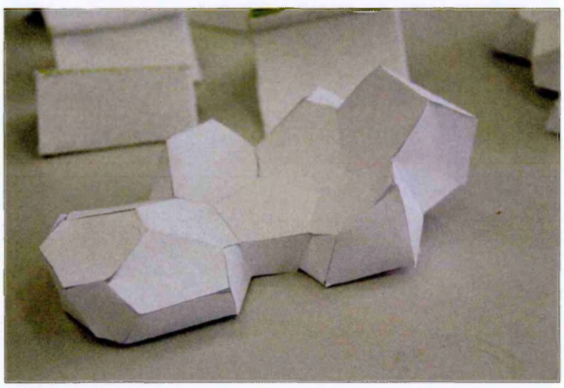
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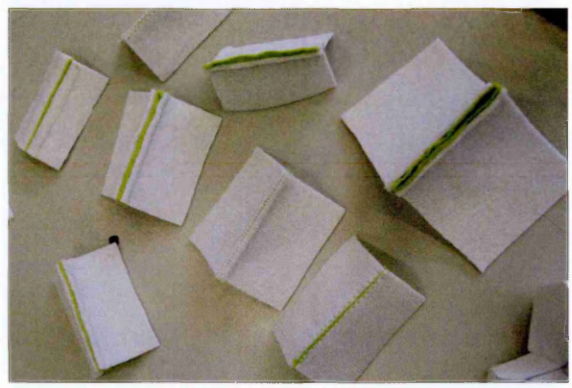
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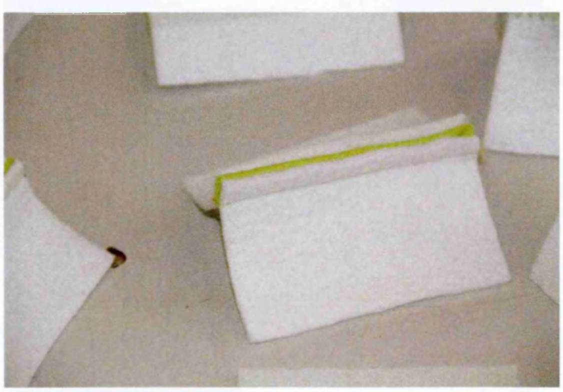
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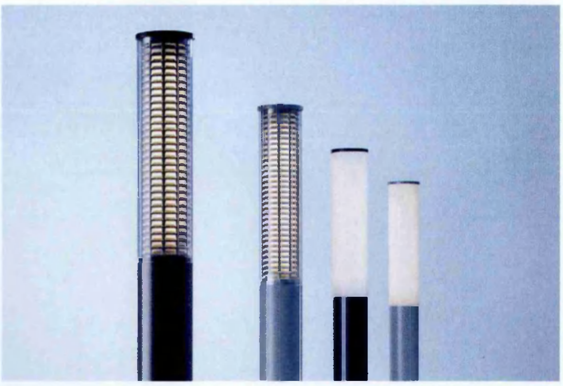
Prototyping example



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As an example, one prototyping process was reconstructed along the development of a light emission reducing lamp for public places (1 & 2).

Identify:
After the client meeting, the team identified the general goals and constraints of the project. These included the reduction of the light being emitted upwards, as well as the production costs.

Collect:
In the second step, one team member collected the existing solutions from the competitors as well as data concerning the clients product line.

Organise:
The gathered information was then organised in different groups and categories. In this examples, the data showed that most of the existing solutions used a combination of several parts, requiring a laborious production process.

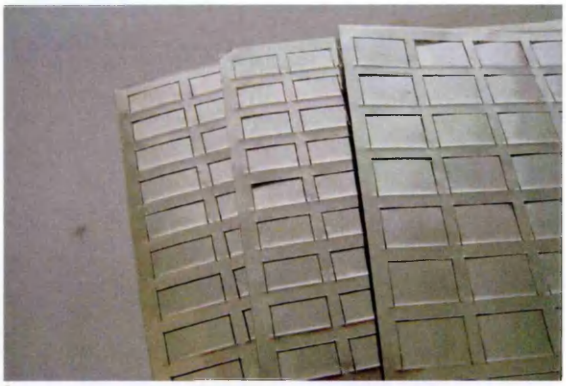
Nummerise:
In this example, the nummerise step was marginal and fused together with the organise step.

Interpret:
In the interpretation of the gathered data, the team came to the conclusion that all the existing solutions trying to reduce the light being emitted upwards, used several rings around the lamp directing the light downwards. In the light of the sudios design standard to find a simple yet elegant solution, this solution was not considered as an viable way. The team then decided to find a way to produce the same effect with only one piece, which allowed for much lower production costs as well as a simpler design.

Also, in this phase, the original problem definition could be refined into more detail. The questions asked, where how to reduce the light emitted upwards using one part and which angle, colour, and material this solution would have to possess. In addition, the team had to consider the type of lamp being used, as it would have being able to evenly distribute the light.

Shape:
Using one aluminium plate, the team then produced many prototypes testing different shapes, colours, and angles to find the optimum configuration. In an early phase, these prototypes were made out of coated paper and cardboard (3, 4). Then, different materials, colours, and angles were being tested (5, 6, 7). Also, investigations were made concerning the production process, what machines and molds would have to be used (8, 9). Then, the prototypes were being tested in a first phase with a photometer. Then the detailed form of the cut out pieces was being investigated, resulting in a trabezoid shape (10). Once the prototypes were refined to a final prototype, they were being send to a governmental test laboratory as to test whether the lamp meets the required demands of the regulatory body.

Expose:
In this example, the finished prototype was being presented to the customer. In other projects, the prototypes are generally presented earlier on in the process to the client. Depending on the clients individual preferences, these prototypes are more or less refined and enhanced with CAD presentations. However, the studio likes to preserve the artistic qualities of the prototypes in the presentation, which can, to a certain degree, be lost in the computer renderings.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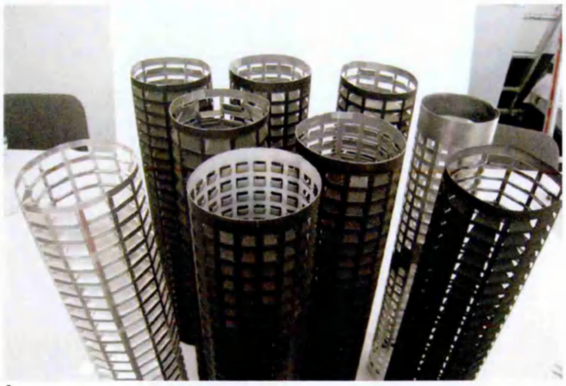
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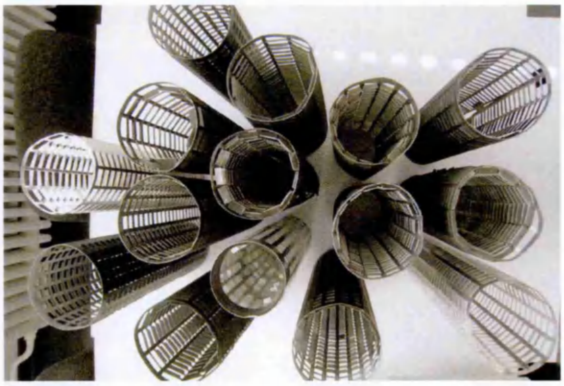
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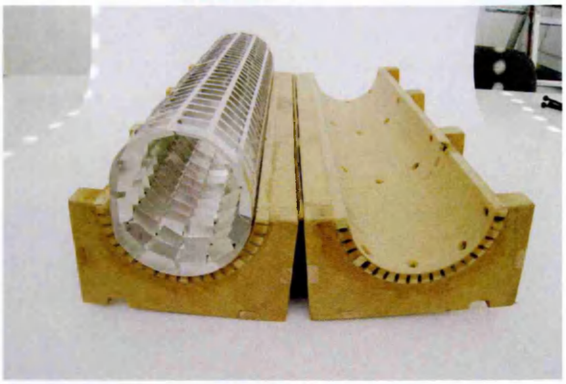
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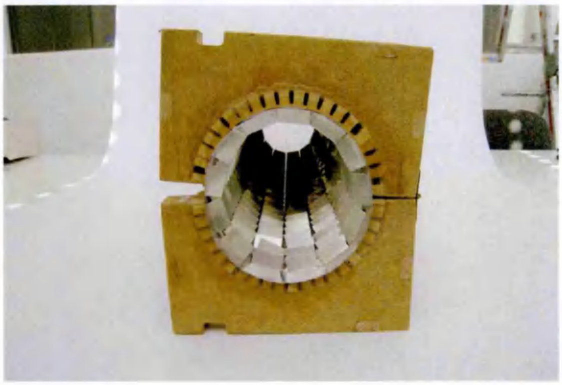
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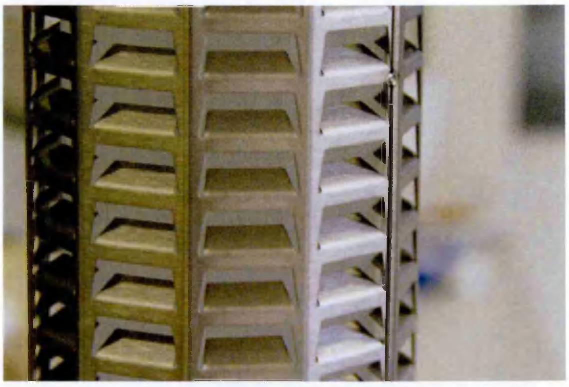
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Appendix: Protoype-focused analysis model

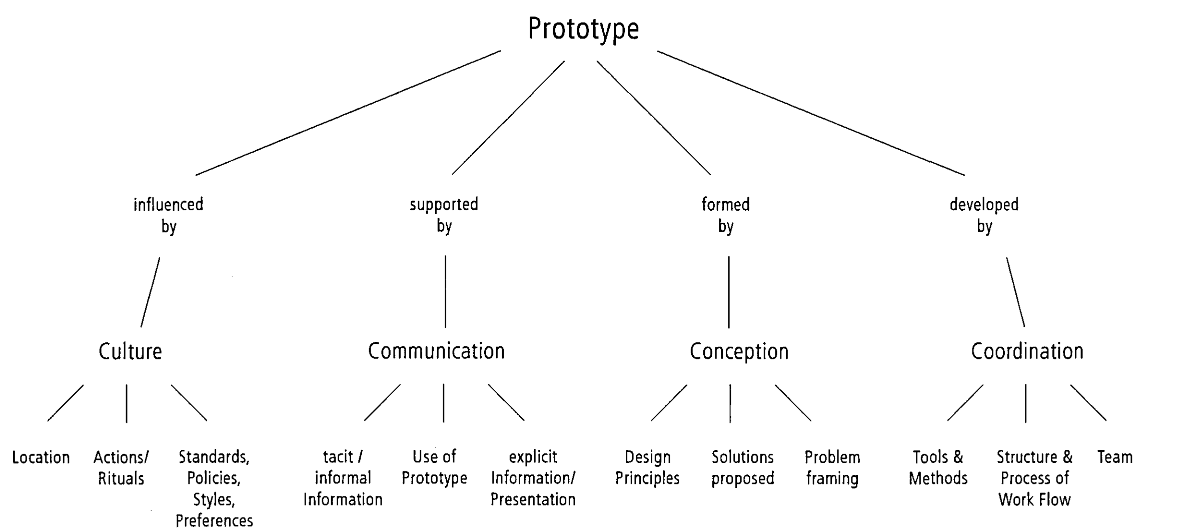

Figure: proposed, prototype-focused analysis model

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Appendix G – field observations Bonbon Graphic Design Studio

Bonbon Design Agency
Analysis

Introduction
Bonbon is a small agency located in Zurich, Switzerland, which is focused on graphic design. It is has been founded in 2003, although the founders already worked together before that. Within the Zurich design community, it is rather well-known. Next to their business, the two founders also teach design at the University of Art and Design Lausanne (ECAL) and the F&F Art School in Zurich. Bonbon recruits their most important customers heavily from the art and media institutions in and around Zurich.

General remarks
In this analysis, I first tried to take a closer look at the dimensions proposed by the contextual inquiry approach: work flow, sequence, artifacts, culture, and physical environment. In a second step, I tried to do the same using the draft of the simplified model I formulated to analyse from a prototype-focused point of view.

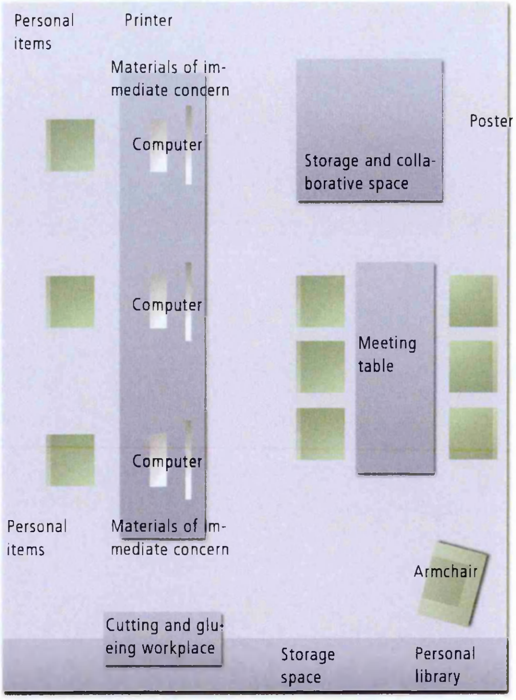
Work flow
As there are only two co-workers (the founders) presently collaborating. Their responsibilities and roles are quite similar, although there are some important differences. On particular projects, the two work closely together with their suppliers and clients. This is in fact their preferred collaboration mode, and they try to pursue it as much as possible. In finding an metaphor for them, they described themselves as the „technician" and the „joker". Although, both claim to have the same roles in general, they identify their individual roles a bit differently. The „technician" is more focused on the development of design concepts and programms, thinking them through in their consequences. The „joker" likes more to question commonly held believes and conceptual distinctions which might emanate in their work. Their collaboration might be well described as a form of constructive conflict. They regularly present each other their current work results in the form of prototypes, sketches, moodboards and the like. In turn, they critize each others works to test their validity. On and off, this might result in personal differences, but both have found strategies to cope with them and turn them into constructive energy. The meetings are mostly held in their studio and are informal in nature.

Sequence
The sequence of the work differs from project to project in its details. On a more general level, they follow roughly proceed in the steps: briefing with the client, gathering of initial inspirations (moodboard), analysis of the different aspects of the project and assignment of individual responsibilities, development of initial sketches and prototypes, internal review of sketches and prototypes (critique), modification and elaboration of prototypes, external review of prototypes with clients and suppliers, further development of prototypes, external reviews as necessary, develpment of final design. The sequence is being triggered by the client briefing. Individual inspirations – which are gathered beforehand in gallery visits, book reviews, etc. – often trigger the ideation phase. The order of the process steps is not fixed in a formal manner, but is used relatively consistent. Breakdowns might happen in the collaboration with the client, when the individual expectancies have not been synchronised during the briefing, or when a mode of collaboration has to be established with new suppliers.

Culture
Both designers prefer an open and honest discourse on their work. Conflict is often accepted as a means to improve the design solution, although it might not always be resolved. They emphasise, that critique, as harsh as it may be, is only allowed regarding the work, not by adressing the individual. Their mutual critique sessions might be identified as specific rituals. Past experiences with an employee and a potential third partner has led them to believe, that this sort of collaboration might only work between the both of them. Breakdowns sometimes happen, when no resolution on a work-related conflict may be found. Power is equally distributed between the both. They emphasize that they value individuality, the application of their own design criteria, and their independence over monetary returns and public recognition (although they won several design awards).

Physical environment
The place is one large loft-like room in a industrial building from the mid 1960ies. It is a tidy and surprisingly quiet place. The individual workplaces are aligned in a straight line, leaving place in the middle for a third co-worker (which at one point was occupied by an intern). All three workplaces are equipped with a (Apple-) desktop computer and a telephone. On one side of the room, a large bookself covers the wall, offering space for a collection of books as well as an archive of the agencies previous work. In a small

niche in the bookself, a work place for cutting an glueing is integrated. In the corner, where the books are being stored, an armchair is standing next to the bookself. Except for two or three spots, the walls do not display any visual stimuli. Only one poster, a recent product for a exhibition, is pinned to the wall, alongside with some minor pieces of printed objects.



The place is a loft-like space, featuring two sides with large windows one side with a bookself and one naked wall.

The bookself serves to store the agencies book collection as well as previous work samples.

We work places are aligned in a single row, leaving one place free between the two designers.

Every workplace is equipped with a desktop computer, a telephone and a lamp. On the side and underneath, there is space for materials of immediate concern.

One corner of the bookself is reserved for the book collection.

A small space within the bookself is designated for cutting or glueing prototypes.

A large table serves as a collaborative space and to store paper samples, as well as large-scaled posters.

Only very few visual stimuli are being displayed on the walls.

Artifacts/Prototypes

One specific artifact was picked to take a closer look at – a prototype for a monography for a photographer. The designers first printed out all the pictures the artist collected for publication in a small size (1). They then cut out the individual pictures (2) and printed A3-sized papers with a display of all the books pages as blanks on them, where they assigned the pictures to the pages (3). The designers then went about to find individual combinations of pictures and series of pictures. At different steps of the development, the prototype was reviewed with the photographer and modified where she saw fit (4). Missing material or other future graphic elements where drawn on the prototype (5). Before and during the process, the artist sent the designers inspirational material, such as postcards with a distinct and desired aesthetic, to clarify her vision or requirements for the product.

The prototype is made in such a manner that it allows the designers to freely reassign and recombine the individual pictures, collaboratively. While offering to faster and more spontaneous make combination choices, the prototype also gives a better impression of and feel for the final form and materiality of the book by executing the initial design on paper rather than the computer screen. The structure represents the conceptual form of a book while scaling everything down. The scaling enables the designers to gain a better grasp of the book as a whole and structure it in a sequence of individual but connected series of photographs. The presentation of the prototype is that of a rough draft. It is more concrete in its image quality than drawings. The decision for this kind of prototype implies that the design of graphic elements and typography will have to be combined with the images in a later stage of the process. It therefore reveals a decision to focus on materiality and the power of the pictures themselves, which might be an implicit design strategy for the book.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Protoype-focused analysis

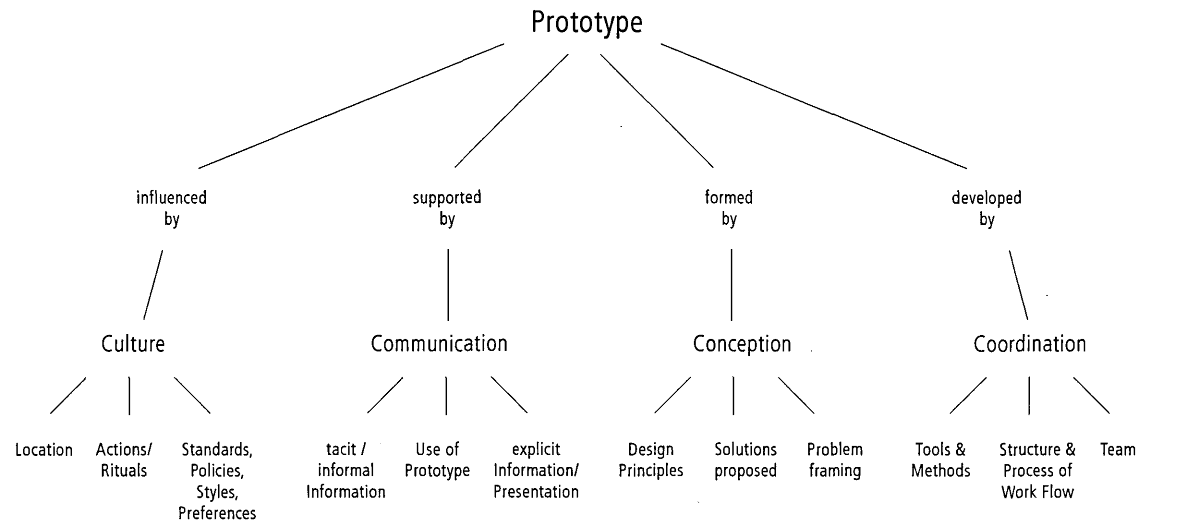


Figure: proposed, prototype-focused analysis model

Using the model of a prototype-focused analysis above, the following data could be gathered:

Culture

Location: The design agency is located in a loft-like room in an old industrial building. The interior is functional but not particularly hip. The furniture seems to consist mostly from second-hand collectibles. The walls are scarcely decorated. Only few personal objects give hints to who might work in the place. It is a very quiet place. No music whatsoever is to be heard. The building is located in an area some miles from the centre of the city. It is quite close to one of the parts of the city, which is considered to be one of the hippest places at the moment.
Rituals/Actions: The two designers cultivate an exchange and critique of ideas in periodical meetings which could be described as constructive conflict.
Standards/Styles/Preferences: The agency has a preference to work closely together with their suppliers (like the print shop or the bookbinder) as well as their clients to develop the most suitable solution for a design problem. They do have a strong tendency towards elaborated typographical solution.

Communication

Tacit/Informal Information: Through its loose parts, the prototype is implying a high importance in the flexibility and momentariness of the arrangement.
Use: The analysed prototype could in its use be – referring to Ferguson (1994) – categorised as a thinking and talking sketch.
Explicit Information: The prototype is explicitly showing the arrangement of the pictures and the overall structure of the book. Explicit information is being given by the inspirational material (the post cards referring to specific graphic elements from a time period) sent by the client. Also, notes written on the prototype (like „cover") give hints to yet missing elements or special functions of individual pages.

Conception

Problem Framing: The prototype shows that the problem of sequencing the series of pictures as well as arranging the individual pictures is a dominant topic a solution has to address. Also, by choosing an approach using a paper prototype instead of developing the concept using the computer shows an awareness for the problem of materiality.
Design Principles: The final design principle used could not yet clearly be discerned, as the prototype analysed was not finished at that time. However sequencing, nostalgic styling, and a special focus to materiality could already be discerned as important design themes.
Solutions proposed: A final solution has not yet been proposed and thus can not yet be analysed.

Coordination

Tools & Methods: Up to this stage of the development, the major tools have been scissors, cutters, and glue sticks. To a small part computers and printers have also been used in preparing the A3-papers with the books layout and the scaled pictures.

Structure/Process: The process and structure of the work flow was divided into a client briefing, an inspirational phase, a first discussion of the inspirations and first drafts, the development of a first paper-prototype, a discussion of the prototype with the client, and an ongoing contact with the client regarding additional inspirations or visual guides.

Team: The team consists of the two designers, the „technician" and the „joker". At different points collaboration is seeked with the client. Also, the designers anticipated to work closely together with the bookbinder and the printers in a more advanced step of the design process.

Appendix H – field observations Stimmt AG

Analysis «Stimmt AG»

Introduction

Stimmt AG is a customer experience consultancy based in Zurich, Switzerland. Currently, 14 consultants and partners are in its employ. Historically, the main focus of the company's activities lays on web-based user experiences, most importantly prototype testing and optimising. To strengthen and enhance its core competencies as well as to address a recent shift in clients' needs, the consultancy aims at developing and implementing a creative methods toolkit. In this context, Stimmt agreed to take part in a study accompanied by the author of this report. The study is investigating the application of design-driven development methods within companies.

The following notations represent the data from two interviews with Marc Blume and Johanna Elster, both senior consultants. Blume has a background in psychology and is responsible for developing, aggregating, and implementing the tools and methods needed by Stimmt's consultants in their work routine. Elster has a background in media studies and serves at Stimmt as a telecommunication specialist in the intersection between user requirements, management and technology. The objective was to gain an overview of the currently employed tools and methods with a special focus on the creation-related process phase. In addition, different dimensions derived from a previously defined prototyping-centred model of design-driven innovation were being explored (see appendix).

Process

Stimmt's core routine is a twofold process. Splitting from a defined target outcome, the process either proceeds to a strategy development or a concept development section. Within these two distinctions, the individual steps are very similiar. The strategy route follows the steps ‚Set up', ‚Understand', ‚Create', ‚Validate & Assess', ‚Focus', and ‚Transfer'. The concept process proceeds through the stages ‚Set up', ‚Understand', ‚Focus', ‚Create', ‚Verify', and ‚Transfer'. Addressing individual clients' needs, the concept phase might or might not be preceeded by a strategy phase. At the end of the two sequences, two additional steps are being conducted: delivery and debriefing.

Set up:	In this first step of the process, the consultants define together with their client the mutual expectations regarding the proceeding, the collaboration and the outcome.
Understand:	The aim of the ‚Understand' phase is to identify and grasp the most crucial problem. This might involve to prioritise or filter out different kinds of problems.
Focus:	During this step, the team defines and prioritises the critieria for the ideal solution to the problem identified in the previous process phase. In the strategy development phase the strategic options are being evaluated. In the concept development phase the most crucial problem areas with the biggest leverage are being defined.
Create/ideate/ prototype:	The team then explores different ideas. The gathered solution approaches are being evaluated. Out of these, a selected few are being prototyped.
Verify:	The prototypes built in the ‚Create' step are then being tested and selected in this phase of the process.
Transfer:	Finally, the verified solution is being implemented at the client's business.

By gaining new insights, each of these steps might make it necessary to revisit a previous step. In fact, in most projects these steps are, according to Blume, being used in an iterative manner. Elster roughly structures these process steps into three distinct phases: a) problem definition, b) creation, and c) testing/verification.

Tools & methods

Stimmt is using a variety of different tools and methods while proceeding throught the individual steps of the solution process. Most often they are using one or more of the following:

Understand:	- Interviews - Observations - Personas - Contextual Inquiry	Create:	- Brainstorming - Bodystorming - Roleplay - Informance (combination of information and performance) - Experience matrix
Focus:	- Requirements analysis - Customer journey - Concept of use - User Stories - User Flows	Ideation:	- Idea wall
		Testing:	- Paper Prototypes (Balsamiq)

As Blume points out, these items represent tools and methods with different depths of articulation. Some of them are being used only on a superficial level, while others might be more elaborated in their application. As a new methodological approach, design thinking has been introduced during a workshop in September 2010. While the consultancy likes to use this method more widely, it is, up to this date, still being used rather inconsistently.

Elster annotates that, while in recent years Garrett's model of five elements of the user experience was predominatly used as theoretical framework, this approach is more and more taking a back seat. This is mainly because Stimmt's projects may be best categorized as strategy or concept/create projects, a distinction which somewhat collides with Garrett's approach. According to Elster, the german ISO 13407 „Benutzer-orientierte Gestaltung interaktiver Systeme" norm has become increasingly important. As of January 2011, this standard has been substituted by the internatial norm ISO 9241 „Ergonomics of Human System Interaction".

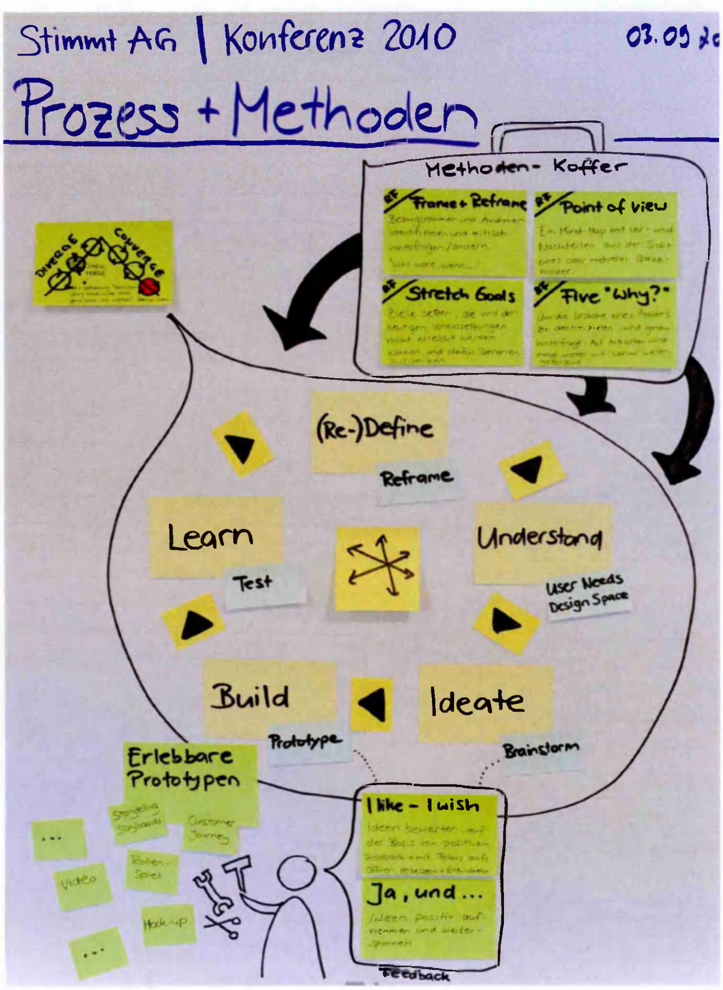
Create/ideate/prototype

In their creation-oriented process phase, Stimmt is using different approaches and methods. One widely used method is the formulation of a problem-specific customer journey, which defines the services, the interactions, and the touchpoint design. As Elster comments, the consultants specifically look for so-called pain-points and delighters within the experience. Another method is referred to as target experience, which defines as an ideal experience the valence criteria that denote the basal emotions the design solution aims to trigger. In user interface design, paper prototypes are being commonly used as a quick and fast means of feedback generation. As Blume points out, even these simple prototypes may provide valueable data and insights to the consultants. Roleplay has also been used in a few cases. According to Blume, these studies, although somewhat limited in their design and validity (because of the artifical research setting), they also give important information about the user's perception.

Elster points out that the change from the understand process phase to the create phase is a rather direct, and at times, fast one. As concluded in Cross (2004) this correlates with the observation that over-concentration on problem definition does not lead to successful design outcomes. As Blume, Elster emphasizes the role of paper prototyping, especially using the mock-up software Balsamiq. She observes that people are capable of extreme abstraction when set in context. When prototyping experiences involving different touchpoints, Stimmt has produced different physical mock-ups in the past. In one instance, the consultants built a shop out of cardboard to give the proband a physical context in which the experience would take place. This somewhat echoes Brodersen et al.'s (2007) suggestion of staging imaginative places to help unlock the creativity while collaborative prototyping. As Elster highlights, this experience was very positively perceived by the test probands.

Another tool used by Stimmt's consultants are user stories. These are distinct from customer journeys in the sense that they focus on individual instances (like the need of a french speaking person to have a french version of a website), rather than on multiple touchpoints.

As mentioned above, design thinking is currently considered as the ideal development approach. In September 2010, the employees received a workshop training at an off-site retreat. The contents taught have been recorded on the flip chart below:



The currently applied design thinking approach as depicted at the methods workshop in September 2010

The chart shows the design thinking model proposed by an institut at the HSG University of St.Gall which collaborates with Stanford's d.school. It denotes a basic iterative process routine composed of the individual steps ,(re-)define', ,understand', ,ideate', ,build', and ,learn'. This routine is located within a more general process, that combines the two directions of divergence and convergence. The process is supported by the methods ,frame & reframe', ,point of view', ,stretch goals', and ,five why'. The model singles out the prototyping as a supporting activity, with individual manifestations, such as roleplay, mock-ups, storyboards, customer journeys, and videos. These are governed by two general feedback rules: ,I like - I wish' and ,Yes, and...'. These aim at giving generally positive and encouraging feedback.

It is notable, that this model does not make any suggestions regarding the development environment and method-specifc properties. According to Youmans (2010) findings, these might, especially regarding the prototyping development, play a crucial role in the individual group's performance. Also, it does not refer to kind of expertise that should be represented within the team, nor to the team work itself. However, these elements might be covered in another resource not identified in these two interviews.

Location/work environment

Stimmt's offices are located in Zurich's fashionable Seefeld borough. They occupy two storeys, a first floor and a basement. The individual rooms are bright and decorated sparsely but thoughtfully. Entering the premises, one passes a cloak room before standing in the midst of a large office with different desks (image 1). Throughout the entire offce, no individual desks exist. Recently, Stimmt introduced the mobile working place, giving every employee a personal locker but no individual desk (image 2). There are, however, different zones and offices for different kinds of work. In the back of the space, smaller office rooms are located, serving for more noisy tasks, such as telephone calls and conferences with clients. Adjoining the large office space, a library with three desks provides a more silent environment (image 3). A small conference room occasionally used to serve as a project room (image 4) until recently. However, as Blume explains, this room is now more often reserved for individual meetings. In the basement, a cosy lounge is serving as a meeting space as well (image 5). Also located in the basement are a large conference room and a spacious area with a fridge, a coffee machine and a large table (image 6).

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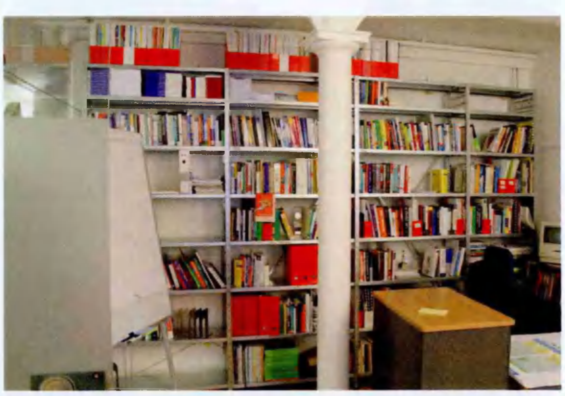

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All the meeting rooms are equipped with different materials such as felt pens, flip charts, post-it notes, etc (7). It is rather noticeable that throughout the offices flip charts do seem to play an important role. In every room, a flip chart is available. In addition, many used sheets are posted to the walls (image 8). This circumstance might point to the conclusion that insights and decisions are often gained in formal conversations. Also, they might point to the use of flip charts as a sort of shared external memory, such as in Van der Lugt's (2005) definition of the ‚storing sketches', as well as Ferguson's (1992) ‚talking sketches' respectively. Also, post-it notes are widely, if not excessively, used (image 9).

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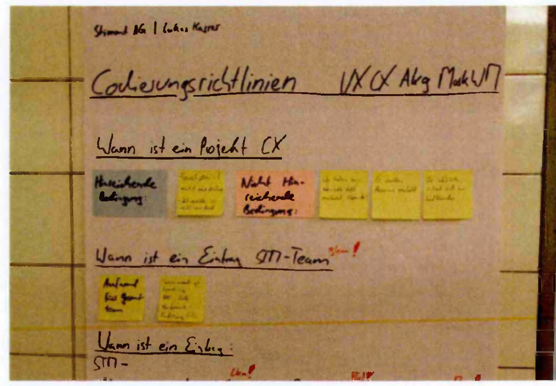

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The whole place is sparsely decorated. However, as Blume points out, the company is making a deliberate effort to give it a welcoming, cosy, and inspiring atmosphere. Some playful details are added to the rooms (images 10 - 14). Blume mentions that those elements mostly emerge in one way or another during individual projects, and are being left behind as a sort of remembrance. As most of the employees and founding partners have a rather analytical mindset, the overall appearance of the office is friendly but sober. According to Blume, these elements represent an effort to bring in a somewhat playful note to the space.

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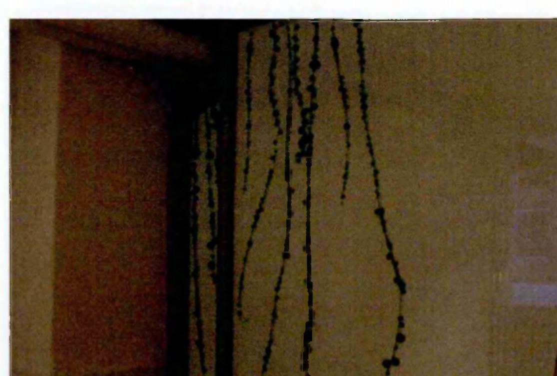

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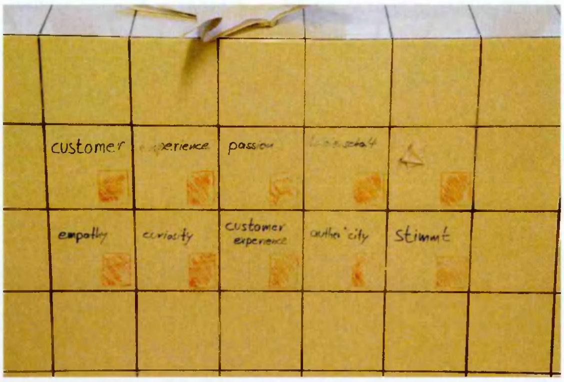

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Standards, values, and rituals

As previously mentioned, Blume describes the company's prevailing mindset as analytical, logic-driven, and factual. The self-perception is characterised by the conception of smart problem solvers, rather than creative idea generators. Their analytical approach is very structured. Some clients even remarked that they would be proceeding too structured, Blume noted. However, they appreciate the need for open, creative spaces within the work routine. Elster points out that their openess might, at times, also be expressed in their notion not to yield to a client's opinion when they are convinced otherwise. This reflects their aim of being and working on a par with the clients and to always be honest. Most of the times, Elster notes, Stimmt is seeked – apart from their expertise – also because of this trait.

Their interactions amongst each other is respectful, as Blume emphasises. The individual co-workers are not being torn out of their way to do some other task. Much rather, they are being asked for a later appointment. Notable is the notion of the founding partners to deliberately diminish perceived differences between them and their employees. The fact that the partners share the same mobile desk policy with the others, thus relinquish their right to an individual office, might illustrate their aim. Elster highlights Stimmt's elaborate recruiting process. Apart from the regular formalities of such processes, the candidates must give a presentation and are interviewed by every member of the firm. This way, the consultancy tries to make sure that the equilibrium and the team spirit of the group will not suffer.

As a ritualistic event might be denoted the shared lunch, which is taken by all co-workers at the large table in the basement. Although it is not mandatory, everybody takes part in this activity. Often, someone brings with them some sort of sweets for the others, which they share during a short break. As another element of Stimmt's culture, their specific playful but professional approach might be mentioned, as Elster proposes. While the consultants maintain a professional attitude and work ethic at all times, fun and enjoyment is not excluded from their routine but fostered.

Collaboration & team work

Mostly, the individual project teams are being assembled according to three criteria: functional aptitude to the related task, professional experience in the appropriate field, and temporal disposability. In their recruitment, the partners originally looked for polyvalent co-workers, being able to take on a variety of different tasks. In recent times however, they have more and more been looking for specialists. New employees are being taught specific consulting and procedure/process management skills when starting to work at Stimmt. The company employs a sort of mentoring or master/apprentice model, putting together senior and junior consultants. The teams vary in their sizes. Most often, a single consultant or two consultants are working on a specific project. Less often, three to four consultant are working together on a single project during the whole time. Some crucial success factors of collaborative prototyping, as proposed by Yeomans et al. (2005), could be identified in the current structure: selection by value, long-term relationships, development of common processes and tools, as well as to a certain degree supporting collaborative arrangements.

The work is mostly being accomplished in workshop meetings. Elster points out that, while Stimmt's consultants bring in their expertise in customer experience design, they depend on their client's specialised knowledge in the respective field of profession. Thus, the collaboration with the clients is intensive. Stimmt's role in this collaboration is to give guidance through the process and to bring in their methodological skills. Usually, between three to five persons join the core group from the client's side. Often these comprise the project manager, as well as a representative of the IT department and the management.

According to Elster, no cellular phones and laptops are being allowed during the workshops, as these would only distract people from the task at hand. Typically, flip charts and post-it notes are being used and photographed in the end as outcome of the meetings. Often, the meetings are being held standing around a flip chart, as this proved to be more dynamic in the interaction between group members, as Elster observed. Such a workshop usually takes around four to five hours of work. In these meetings, the prototypes, for example the interface mock-ups, are being produced on a screen. The discussion occuring around them is most often limited to functional or technical details. This might be due to the individual, specific expertise of the client's group members.

Example

During the interview, one example was discussed in more detail: The largest Swiss telecom provider commissioned Stimmt with the design of a customer experience optimising different key processes when ordering or requesting support for the Swisscom TV product. The aim of the project was to provide a positive overall customer experience with the company's support services as well as to reduce the related operational costs. Those goals were to be reached by designing the individual touchpoints along the customer journey.

The consultants started out by identifiying the existing customer journey for typical procedures. In a two-day workshop, they then defined a first draft of the ideal customer journey as the desired project outcome. In the third step, individual prototypes were being produced. These included, for example, such diverse elements as process models, communication policies, or letters to customers to be sent by the support services department. These prototypes were then being tested with study participants in roleplays. In one roleplay, the customers reactions to an informational letter regarding changes in their voicemail settings and the ensuing process was being tested. Three different kinds of letters were presented, varying in their wording from casual to technical. Then the participants were taken through the other touchpoints along the customer journey, such as the website's information page and the text message received on their mobile phones. The roleplays were conducted along a predefined script. At each step of the process, the participants were asked whether they understood the instructions contained in the individual communication means and how they perceived them emotionally. With the data gathered, a workshop was held to optimise the previously defined customer journey. Based upon the altered journey, a styleguide was being formulated. As the final step, a pilot study was being conducted.

Discussion

This report tries to depict the solution development approach at Stimmt as it represents itself today. As it is based on only two interviews, it may only be understood as a rough outline of some elements of this approach. Thus, the limits of its interpretation have to be emphasised. However, a few insights and focal points for the further conduction of the study may be identified. As the data shows, Stimmt has a heavy notion towards analytical and logic-based skills. Furthermore, prototyping as one main activity of design-driven solution development is being executed by default. Also, the purposeful arrangement and design of the work environment might be a point which could be further investigated and optimised for creation-oriented tasks.

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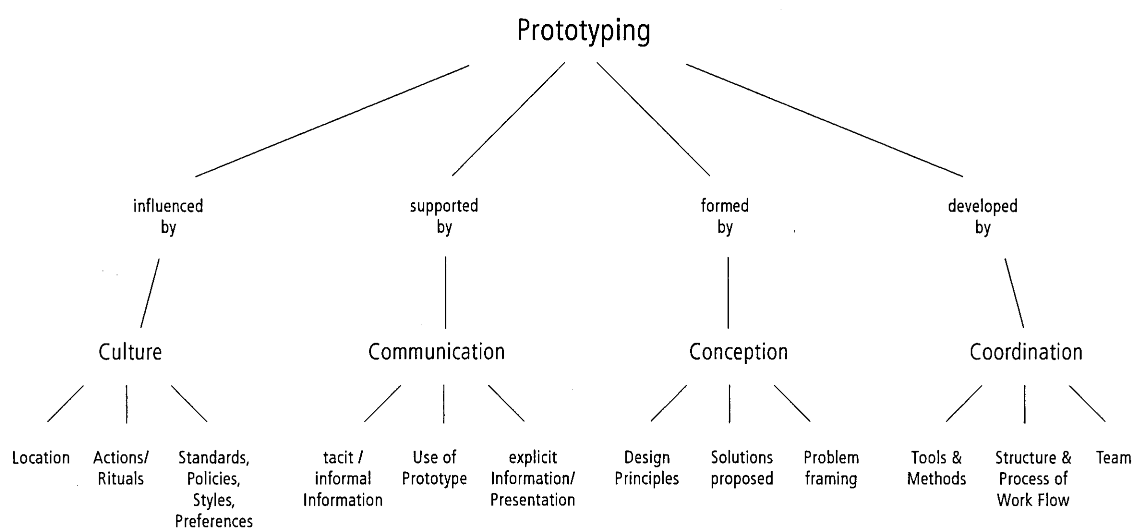
Appendix: Protoyping-focused analysis model



Appendix G – field observations Tromp Research Group, Princeton University

Prototype-driven Research at the Tromp Research Group of Princeton University

Introduction

The Tromp Research Group at Princeton University is one of the most published research group in the field of theoretical and computational seismology. Within this field, the group develops fundamental theories as well as it works on a great variety of projects aiming at a specific practical application. These projects range in their objectives as far as from defining form and behaviour of magma chambers to detecting military warfare like mines or nuclear weapons. The research groups focus is not only restricted to earthly phenomena, but can also include extraterrestrial investigations, such as solar or lunar activities. For this study, the author analysed the tools and process used in a specific project aimed at the theoretical and computational formulation and testing of a theory to define form, location, behaviour and influences of vulcanic magma chambers.

Process

In the first step, the main objectives of the study were being defined. Then, the relevant theoretical background was gathered. Upon the gained insights, the researchers formulated their own theory and an algorithm, which represented their thoughts. This algorithm is regarded as the actual prototype their work would evolve around in the next steps. All the work up to this point was written down in an accessible file, which was to become the final article the research group intended to write. This file served also during the following steps as a shared document for collaboration. The algorithm was then transformed into an application, programmed by the researchers (in XCode, Fortran). A finite element modelling tool (Cubit) was then used to build the first three-dimensional model of the topographic area, which the research focused upon. This model was then imported into another application (Abaqus), which computes deformations in finite element models and which enables to define the individual behaviours of different materials encountered in the geological setup of the vulcanic region. The data was then being converged with the self-programmed application from the research group, and different iterations of tests and adjustment of the algorithm was being performed. In between the different steps, an output application was being used (Paraview) to visualise the individual results. The findings were then implemented into the writing of the article, which was eventually sent to the relevant scientific journals for review, and into a poster for the display at conferences.

Tools & Artifacts

Article: During their research, the MSWord-document served the group as a shared file in which the would write in their findings in the individual stages of the study. The researcher interviewed printed out a hard copy of the article to work independent of computer access on the ideas represented in the paper.

Algorithm-based Application: To make their algorithm usable for further testing and data-computation, the researchers programmed their own application using XCode.

XCode: XCode is the Apple System-based programming editor used to write the researchers application for further computational tests and iterations of the algorithm. For this project, the researchers used the programming language Fortran.

Cubit: Cubit is a finite element modelling application used to build three-dimensional models and to import topographical data.

Abaqus: Abaqus is an application used for finite element deformation. It offers the ability to simulate the individual behaviour of different materials in an topographical situation.

Blackboard: The blackboard is used for individual research work and for collaborations. In collaborative settings, it was mostly used the work on theoretical ideas together with the head of the research group, Professor Tromp.

Poster: The poster is used to present the final finding to the scientific community at conferences.

Collaboration

The collaboration within the research group is being organised upon the individual strengths and abilities of the group members. For the most part, theoretical development and programme direction is a task performed by the professor, the research associates or the postdocs. Programming, testing and iterating is then being performed by research associates, postdocs, and graduate students in constant dialogue with the head of the group. Normally, the graduate students are being relatively closely guided by the professor, the research associates, and postdocs. The group has regular group meetings as well as lots of informal chats. When not collaborating with other universities, the group works colocated on the same floor.

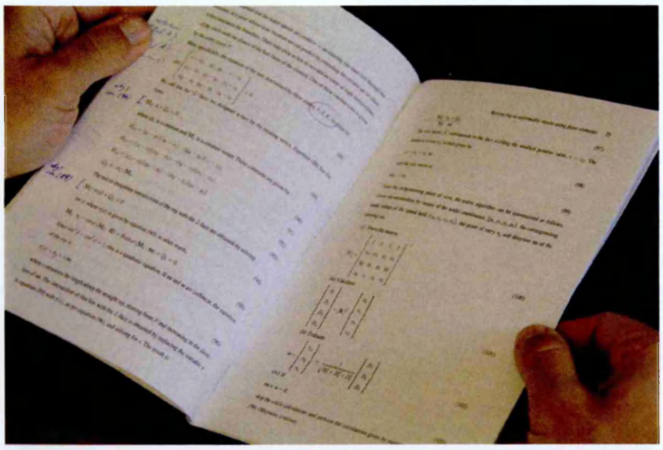
Culture

The culture being lived within the research group is quite casual. The interaction with the head of the group is charatericed by the interviewee as very informal, amicable and comradly. There are no formal or informal restrictions concering clothing or work schedule (altough a minimal work time is formally defined, but not enforced, as all the group members work longer than required). The working environment takes place in a building dating back to the early 20th century, but has been completely modernised in the past three years. A lot of cultural and sporting activities are being offered by the university, which has extensive athletics facilities.

Conclusions

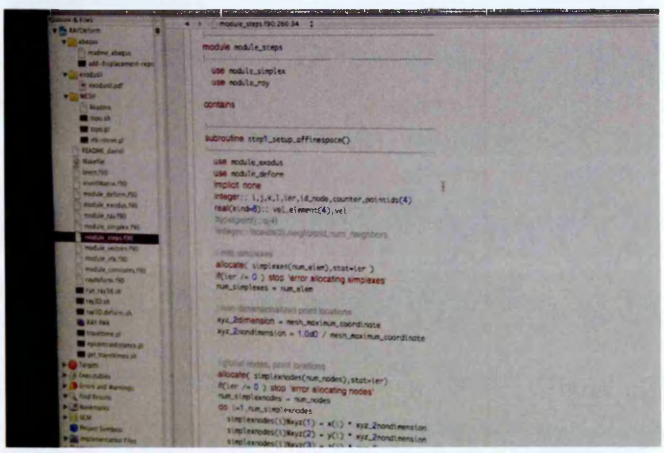
In a broad sense, the research groups use of protoypes does seem quite similar to the mode of work of designers. As their main prototype is an algorithm based upon a relatively complex set of mathematical formula, they made it more tangible (or testable) in different forms, such as a software one of the researchers programmed to represent the algorithms functions, or a model of the topographical situation found at a selected site to test the underlying hypotheses in a real world setting, which might also be viewed as a kind of sub-prototype. Their collaboration is quite straight forward and the roles quite clearly defined and split up, although they might not be fixed to a specific individual. The article, which is to be published and which the researchers work collaboratively on, seems to serve as a sort of unifying artifact, which makes the purpose and aim of the project clear and understandable to everyone involved.

Picture Analysis

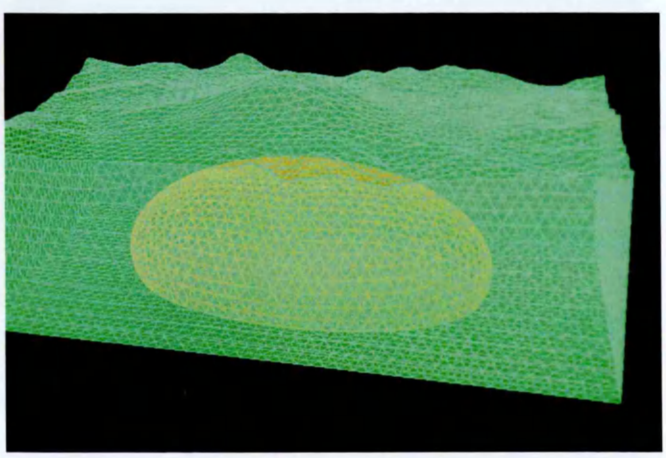


The algorithm, the prototype: The main prototype which was to be developed and refined during the research groups work, was the actual algorithm representing the underlying theory.

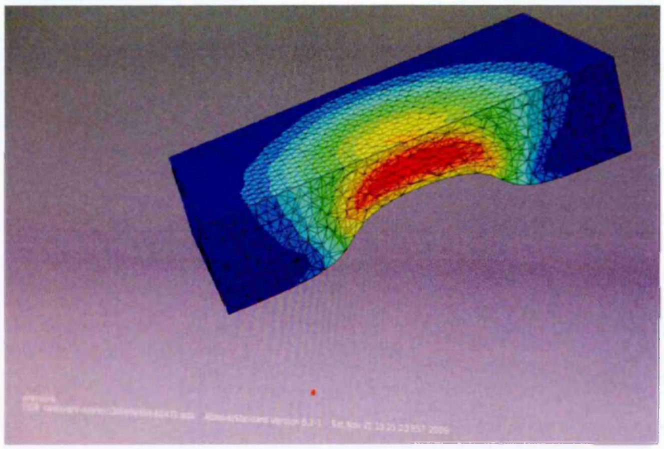
As a work in progress, a shared file of the article to be written, was used by the group to collaborate on the different topics, such as scientific background, theory/hypotheses, testing, and conclusions.



The programm code: For further testing and computing of the algorithm, the researchers programmed their own application representing the algorithms operations.



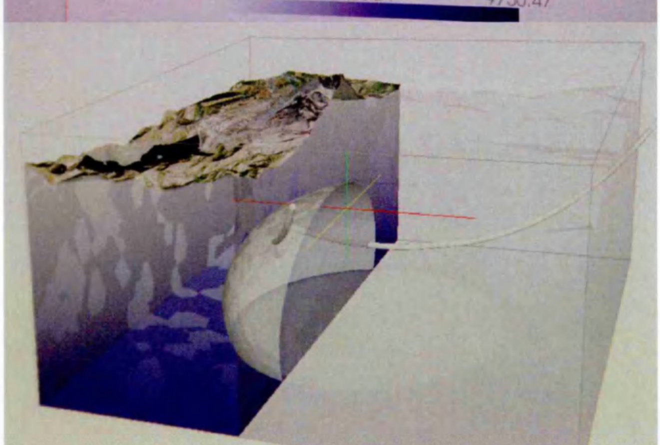
The model: A model of a specific geographical situation is being represented in a finite element model using Cubit, a modelling software.

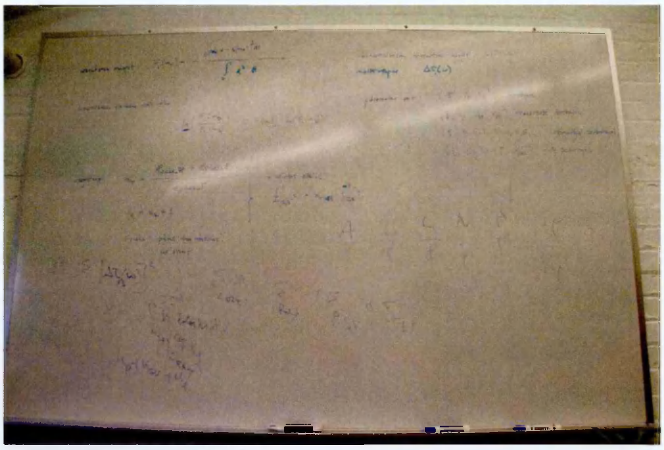


The deformation: The software Abaqus is used to simulate the behaviour and deformation of different materials of the earths surface.

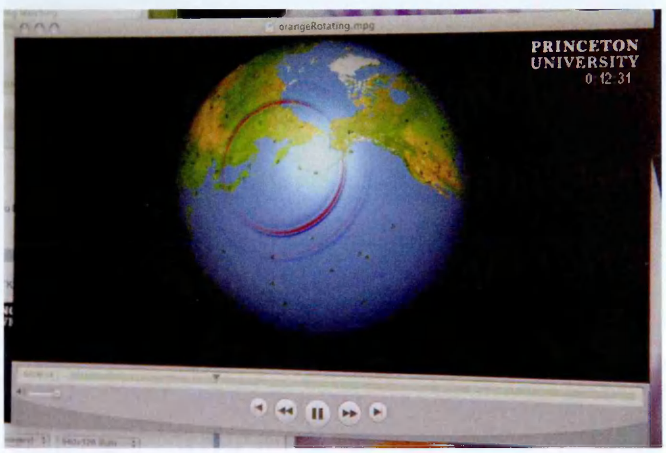
The visualization: Using paraview, the algorithms results may be visually represented in the topographical model.

Compared to the text-based representation of the computed results, the visual form is much faster and easier to understand.

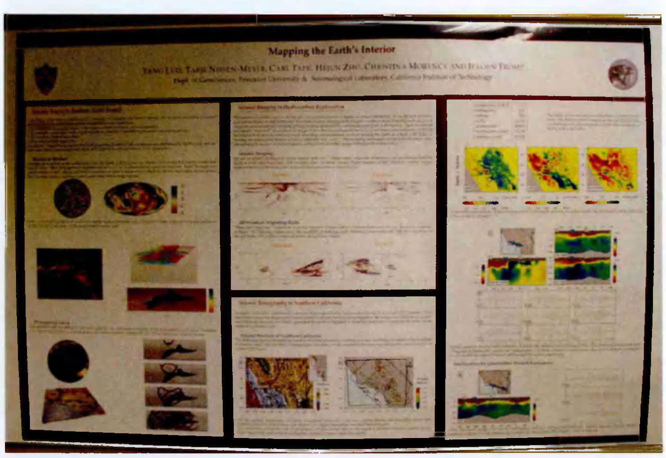




The blackboard: During the whole process, informal meetings in the offices occur spontaneously. The blackboard then offers a unobtrousive possibility to work on a specific mathematical problem together (mostly between the head of the research group and a research associate or postdoc).



The animation: For certain applications, animated visualizations are being produced. In this instant, the main use is to give up-to-date informations of earthqukes taking place around the world. (The picture shown left stems from another project of the group)



The poster: Mainly for scientific conferences, posters of the performed study are being made to communicatie the accomplished work to the relevant scientific community.

Cultural hints: Throughout the departments rooms, small signs of present and past collaborations are informally being displayed (here as a sticker on a door), or as pointers to a specific mindset about what computers to use.

Work Model

	Tasks performed	Tools used		Collaboration
	Overviewing scientific background	Libraries / Online resources	Article	formal & informal meetings
	Formulating theory/hypotheses	Word Processor		
Iterations	Defining algorithm			Blackboard Discussions
	Building topographical model	Cubit		
	Simulating deformations	Abaqus		
	Testing algorithm	Self-programmed software / XCode (Fortran)		
	Visualising results	ParaView		
	Drawing final conclusions	Word Processor		
	Presenting findings	Adobe Illustrator Word Processor	Poster	

Appendix J – interview analysis Hans Schreiber, Forster-Rohner AG

Expert Interview
Hans Schreiber

Preliminary notes
The interview was conducted in early April 2010. It was set up as a semi-structured interview. As a preparation, the main topics of interest were defined: inspiration, process, trends, culture, prototyping, and collaboration. For each topic different questions were formulated in a following step. The interview was then audio recorded and transcribed for further analysis. In a first step, the interviewees statements have been grouped together in the predefined categories and written out for better readability. This last step was being done according to the proposed first phase of analysis by the grounded theory approach of ‚open coding' – but with the destinction of the use of predefined categories based upon the literature research performed so far.

Background information
Hans Schreiber is head of creation at Forster Rohner AG, a swiss SME. Forster Rohner AG was established over 100 years ago and is today being considered as a innovation leader in the embroidery industry. Hans Schreiber has been working at Forster Rohner AG for the last ten years, being promoted to creative director in 2008.

Analysis

Inspiration
In order to find inspiration, Schreiber states, that the outset of every process has to very open. The narrower the brief is formulated in the desired goal, the less creative he perceives his process. He finds it much less inspiring if the customers knows exactly what they want. The company Schreiber works for Forster-Rohner AG, owns a large archive of designs and production techniques with over 400'000 items. This archive serves as one major inspiration in his work, where he may draw upon the design work and production history dating back as far as 125 years. Schreiber also collects also a lot of inspriation from his intense travel activity and the exchange of thoughts with customers. In his immediate work environment, he is free to design his workplace and surround himself with inspiring material and objects as he likes.

Process
The process Schreiber uses to achieve the project goals is only structured in a very loose sense. Starting with the clients requirements, he looks first for inspiration. He then starts the ideation process with an early trial and error phase in which he explores and testes many different possible directions. The results of the work being during this step inspires him for further tests and ideas. Also, during this phase of the process, he may visit the archive or the production facilities colocated at the headquarters to gain deeper insights, refine existing ideas or inspire new ideas. He emphasises the importance of this colocation of management, marketing, creation and production. The close contact to the crafts-oriented production culture helps his creation team not only to inspire its own work, but also avoid a ‚L'art pour l'art'-attitude.

Schreiber also seeks the close collaboration with his customers. This collaboration may include in a preliminary phase extensive talks, visits of the fashion designers shops or even shared activities for inspirational purposes such as the visit of an exhibition or museum. During the development phase, Schreiber is maintaining close contact with the customer and his creation team, sending back and forth sketches several times a week.

While stepping through the individual steps of the process, Schreiber heavily relies on his expertise and vast arenal of different methods gained in his years in the field of textile creation. To avoid conceptual repetition, he reflects the process and consciously seeks new challenges and rethinks individual steps of the process, giving up existing security by the applied work routine in solving problems. This is sometimes achieved by exploring extreme ideas to inspire his work.

Trends

Watching the trends emerging in his field of profession is viewed as a necessity by Schreiber. But he adds that following only the trends in the fashion industry would prove counterproductive for Forster-Rohner AG, as their designs needs to be ready well before the fashion designers begin their work. So, in a sense he needs to anticipate emerging trends on an average of two years ahead of the fashion designers. Therefore, he observes many different social dimensions such as politics, science or culture. He then tries to aggregate those observations to some sort of intrinsic knowledge about what influences are becoming important in his line of business the next years. These trend forecast is then being reflected against Forster-Rohners brand values and corporate history to evaluate the strategic focal points.

Culture

Forster-Rohner's corporate culture leaves a lot of autonomy for creational freedom. Schreiber is allowed to design his and his teams work environment according to his own needs, surrounding themselves with a lot of inspirational materials and objects. The company is proud of its reputation as well as its successful history, which in turn reflects in its brand values. These values are tacitly being embodied in the company's produce. New innovations correlate to the corporate culture at Forster-Rohner AG as a part of the brand strategy. New designs and innovations are being tested against the companies historically developed values. Corporate history influences what is being developed and designed. Schreiber also points out that the corporate culture is rooted in its craftmanship and carried by an innovative attitude, open-mindedness and connectedness in a global network by the company's owner family. He finds it important for his work, that the company's values correlate to his own values.

Problemdefinition

Schreiber prefers a very open definition of the brief or the problem. He finds the results much less creative, when starting from a very specific client's brief.

Prototyping

Prototyping starts at an very early stage. Right after the initial inspirational phase, Schreiber starts to explore different possible ways. These may be explores by drawing ideas on paper or by experimenting with inspiring fabrics. The development is being done in a very hands-on way, often characterised by a close collaboration with the production department.

Collaboration

Collaboration is taking place mainly in three different dimensions: within the team, within the company, and with the customer. The core team is represented by Schreiber's creation department. The sketches and moodboards etc. are being done there. Within the company, Schreiber and his team work together with the different departments, mosty prominently with the production department. As the third party, Schreiber closely works together with the company's customers, the fashion designers. No formal collaboration is being followed with the end customers of the fashion designers.

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